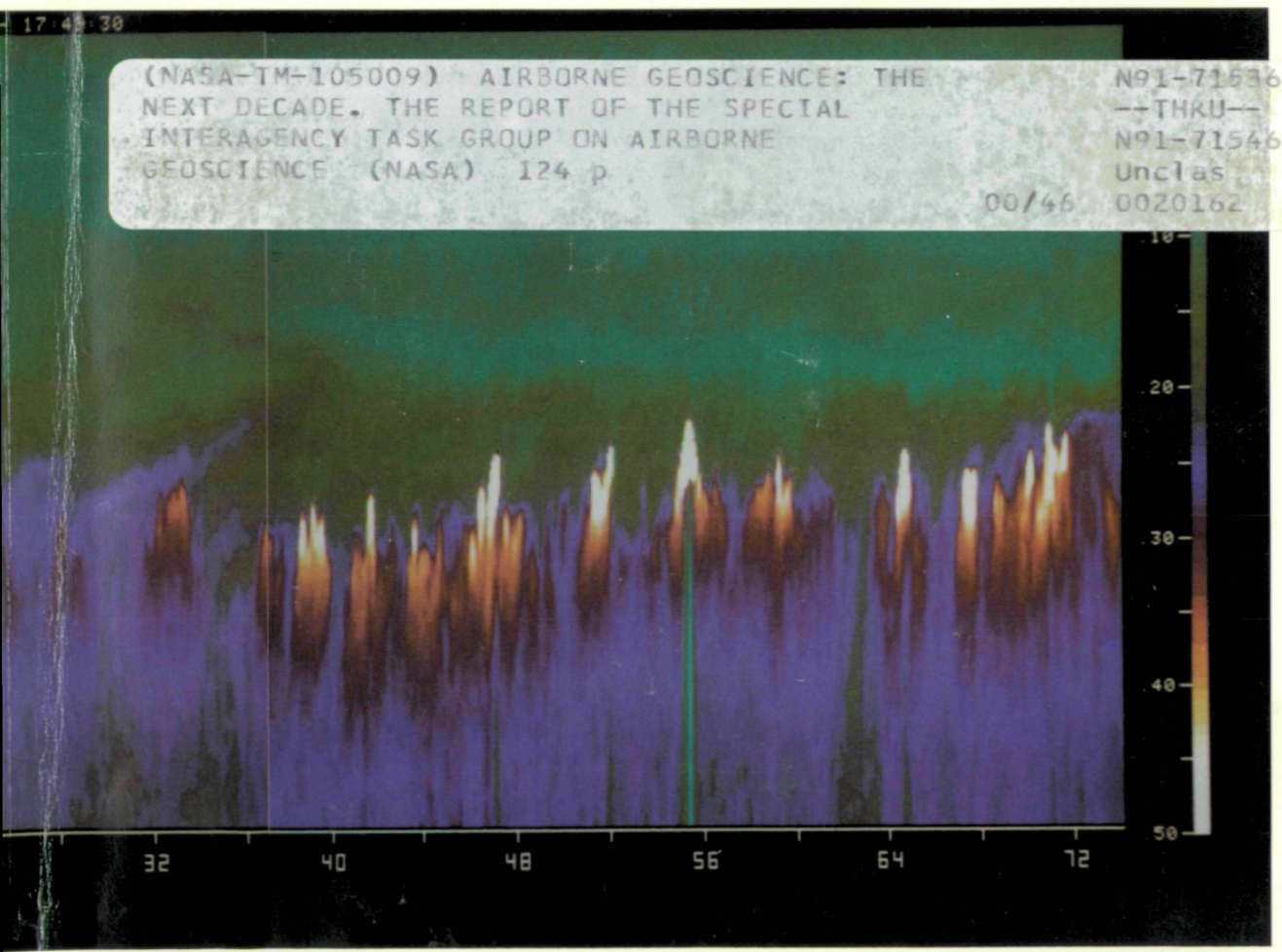
Airborne Geoscience: The Next Decade

The Report of the Special Interagency Task Group on Airborne Geoscience



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COVER:
The structure of the planetary boundary layer observed using a downward-looking airborne lidar. These measurements were made over the Atlantic Ocean during the Frontal Air-Sea Interactions Experiment (FASINEX) on February 21, 1987.

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February 1989

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Preface

IN JANUARY 1985, informal discussions between representatives of the three Federal agencies most involved in airborne geoscience—the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF)—led to the recognition of several areas of common concern about the roles of aircraft in the scientific programs of these agencies. Among these concerns was the fact that the importance of airborne geoscience is not always clearly recognized nor is its scientific output always evident to the various management hierarchies involved. It was also clear that the various agencies have common interests in sharing their facilities for the acquisition of airborne geoscience data.

To further these common interests, an informal Interagency Steering Committee for Airborne Geoscience was formed. The committee, composed of representatives from NOAA, NASA, NSF, the National Center for Atmospheric Research (NCAR), the Air Force Geophysics Laboratory (AFGL), the Office of Naval Research (ONR), and the U.S. Geological Survey (USGS), convened a workshop in Boulder, Colorado, in August 1985, for user scientists and aircraft facility managers to review scientific results and to suggest improvements in the programs of the different agencies. The workshop led to several follow-on activities, including establishment of the *Airborne Geoscience Newsletter*, the acquisition by NASA of a DC-8 aircraft to replace the Convair 990 destroyed in August 1985, and active planning of further workshops.

The Second Airborne Science Workshop was held in Miami, Florida, in February 1987. Reviews of the scientific results of investigations with active, passive, and *in-situ* sensor systems were conducted during the first $2\,^1/_2$ days, with the afternoon of the third day organized as a panel session on the needs of airborne science for instrumentation and airborne platforms, and on improved cooperation among agencies and universities.

At a meeting in April 1987, Committee members presented a review of the second workshop's results to key managers representing NOAA, NASA, NSF, NCAR, and USGS. The major recommendation at the meeting was for a detailed study, to be conducted by aircraft facility managers and user scientists, to refine the workshop's general recommendations concerning the needs of airborne science. In response, the Interagency Steering Committee convened a Special Interagency Task Group of scientists and facility managers from these agencies and several universities to perform the study, reported herein, during the latter half of 1987 and early 1988. The objectives of this study were to identify requirements for improved instrumentation and platform capabilities in response to scientific needs, and to propose

enhancements of procedures and interagency cooperation. The Task Group's expertise covered *in-situ*, passive, and active sensing instruments applied to atmospheric, oceanic, terrestrial, and cryospheric processes.

The strategy of the Task Group involved reviewing major geoscience goals and relating these goals to airborne observational requirements. These requirements were then compared to current capabilities, and needed improvements in instrumentation, airborne platforms, data management, and program coordination were identified. Meeting in Boulder, Colorado, in August 1987; in Annapolis, Maryland, in October 1987; and in Palo Alto, California, in February 1988; working both in plenary session and in smaller groups, the Special Interagency Task Group generated this report. The contents of this report represent the positions of the members of the Special Interagency Task Group and do not necessarily represent the positions of any Government agencies.

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Key: A- Atmosphere
O- Oceanography
L - Land
C - Cryosphere
I - Instrumentation
F - Facilities/Administration

**Interagency Steering Committee on Airborne Geoscience*

Table of Contents

1.0 Introduction 9

1.1 The Role of Research Aircraft in the Geosciences 9
1.2 New Directions in Geoscience 10
1.3 Report Overview 11

2.0 National and International Geoscience Programs Employing Research Aircraft 13

3.0 Current Research Aircraft Capabilities and Uses 19

3.1 NASA Research Aircraft 19
3.2 NSF/NCAR Research Aircraft 21
3.3 NOAA Research Aircraft 22
3.4 Other Agencies 22

4.0 Atmospheric Science: Scientific Challenges and Airborne Observational Needs 25

4.1 Climate 25
4.2 Atmospheric Chemistry 26
4.3 Atmospheric Dynamics 29
4.4 Radiative Processes 37
4.5 Cloud and Precipitation Processes 38
4.6 New Airborne Platforms Needed by Multiple Disciplines Within Atmospheric Science 40

5.0 Ocean Science: Scientific Challenges and Airborne Observational Needs 43

5.1 The Scientific Challenge 43
5.2 Ocean Science: Airborne Observational Needs 45

6.0 Terrestrial Science: Scientific Challenges and Airborne Observational Needs *49*

6.1 Biology and Ecosystem Science: The Scientific Challenge *49*
6.2 Biology and Ecosystem Science: Airborne Observational Needs *50*
6.3 Hydrology: The Scientific Challenge *52*
6.4 Hydrology: Airborne Observational Needs *53*
6.5 Human Cultural Phenomena: The Scientific Challenge *53*
6.6 Human Cultural Phenomena: Airborne Observational Needs *54*
6.7 Geology (Lithospheric Science): The Scientific Challenge *54*
6.8 Geology: Airborne Observational Needs *56*

7.0 Cryospheric Science: Scientific Challenges and Airborne Observational Needs *59*

7.1 Sea Ice Studies: The Scientific Challenge *59*
7.2 Sea Ice Studies: Airborne Observational Needs *61*
7.3 Snow Studies: The Scientific Challenge *62*
7.4 Snow Studies: Airborne Observational Needs *63*
7.5 Land Ice Studies: The Scientific Challenge *63*
7.6 Land Ice Studies: Airborne Observational Needs *64*
7.7 Permafrost Studies: The Scientific Challenge *65*
7.8 Permafrost Studies: Airborne Observational Needs *66*

8.0 Basic Research-Aircraft Systems: Technical Challenges and Needs of Geoscience *67*

8.1 Aircraft Positioning and Navigation Systems *67*
8.2 Aircraft Communications and Telemetry Systems *69*
8.3 Aircraft Data Systems and Data Management *70*

9.0 Interagency and Agency-User Considerations *73*

9.1 Interagency Collaborations *73*
9.2 Institutional Limitations *73*
9.3 Recommendations for Interagency and Agency-User Cooperation *74*

10.0 Recommendations *75*

10.1 Airborne Platform Recommendations *75*
10.2 Airborne Instrumentation Recommendations *77*
10.3 Positioning Systems Recommendations *83*
10.4 Communications Systems Recommendations *83*
10.5 Data Systems Recommendations *84*
10.6 Data Management Recommendations *84*
10.7 Interagency and Agency-User Cooperation Recommendations *84*

Appendices

Appendix A Typical Annual Flight Activities

Appendix B Research Aircraft Performance Characteristics and Instrumentation

B-1. NCAR Aircraft

B-2. NASA Aircraft

B-3. NOAA Aircraft

List of Illustrations

Figure 4-1	Antarctic Ozone Measurements	28
Figure 4-2	Lidar Observation of the Boundary Layer	30
Figure 4-3	Radar Reflectivity and Doppler-Derived Winds in Hurricane Gloria	32
Figure 4-4	Tropopause Fold Observations Using Airborne *In-Situ* Sensors	34
Figure 4-5	Tropopause Fold Observations Using an Airborne Remote Sensor	35
Figure 4-6	NASA/NOAA Arctic Haze Measurements	37
Figure 4-7	Raindrop Spectrometry in the Joint Hawaiian Warm Rain Project	39
Figure 5-1	Research Aircraft Contributions to Gulf Stream Studies	44
Figure 5-2	Chesapeake Bay Salinity Study – The Advantage of Airborne Mapping	46
Figure 6-1.A	Forest Canopy Lignin Concentration	51
Figure 6-1.B	Nitrogen Mineralization of Soils	51
Figure 6-2.A	Magnetic Anomalies in the Sea Floor	55
Figure 6-2.B	Earthquake Epicenters on the Sea Floor	55
Figure 7-1	Sea Ice Observation Techniques	61
Figure 7-2	Radar Sounding of Glacier Ice	65

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Introduction

1.1 The Role of Research Aircraft in the Geosciences

RESEARCH AIRCRAFT have a long history of contributing to advances in atmospheric, oceanic, terrestrial, and cryospheric sciences. Without the use of aircraft, much of the recent rapid increase in mankind's understanding of the environment would not have been possible. The importance of research aircraft to Earth systems science, or "geoscience," arises from the inherent speed and three-dimensional maneuverability of airborne platforms and the way aircraft can complement other types of environmental observations.

Consider first the role of research aircraft in making *in-situ* observations in the atmosphere. This most traditional use of research aircraft, wherein sensors are flown directly into critical locations in the atmosphere, has set the pace for progress in several areas of the atmospheric sciences: air flow dynamics, air chemistry, radiation, cloud/aerosol physics, and air pollution. Aircraft carrying *in-situ* sensors have allowed fundamental discoveries concerning the correlation of physical quantities in both quiescent and stormy conditions.

An additional, crucial use of *in-situ* data gathered from aircraft is as calibration standards for surface-based or spaceborne remote sensors. Without the "truth" provided by airborne *in-situ* measurements, the validity of remotely sensed data would remain unverified. Alternatively, by measuring quantities that cannot be determined remotely, airborne *in-situ* sensors provide complementary data for use with data that can be remotely gathered.

A second important use of research aircraft is as vehicles for the delivery of deployable sensors. In the atmosphere, the dropsonde (a sounding device dropped from aircraft for measuring temperature, humidity, and winds) provides information on the structure of storms at sea. In oceanography, surface buoys and expendable bathythermographs dropped from aircraft provide both surface and subsurface data. In the terrestrial sciences, land-based instruments are deployed from aircraft into remote continental regions.

The third application of research aircraft is as platforms for remote sensors. The aircraft's ability to quickly carry these sophisticated instruments to the region of interest (e.g., a storm, a polluted basin, a region of sea ice, drought-stricken crops, a warm ocean current) and its ability to remain on station for several hours make it an ideal platform. Here again the range of application includes all domains: atmosphere, ocean, ice, and land. Both ocean and land biological productivity can be determined from airborne sensors. Ocean surface temperature, wave roughness, and ice thickness can be mapped quickly over large areas of remote seas. In the atmosphere,

airborne lidar and radar are beginning to provide a more detailed picture of storm-cloud and boundary-layer structure. Airborne spectroscopy provides information on trace-gas and particle concentrations at altitudes above the aircraft.

An extension of this activity involves the use of aircraft for the development of remote sensors that will later be placed on orbiting satellites. Like the satellite, airborne instruments can look down on the atmosphere, ocean, and land from significant altitudes; but unlike its spaceborne successor, the airborne instrument can be quickly retrieved and modified. Virtually all of the spaceborne sensors contributing to the recent rapid progress in the geosciences were developed first as airborne instruments.

When viewed together, the portion of our environment that can be investigated with research aircraft is very large. It includes:

- Stratospheric chemistry and dynamics
- Tropopause and jet stream mixing processes
- Free-tropospheric storms and clear-air dynamics and chemistry
- Boundary-layer turbulence and chemistry
- Land surface moisture, biota, and geology
- Ocean and lake surface chemistry, biology, temperature, color, and wave activity
- Sea ice, snow, glaciers, and permafrost (the cryosphere)
- Ocean subsurface hydrographic structure, biological structure, and currents.

The geographic domain is similarly great. The expanse of the geosphere from pole to equator that has been studied from aircraft includes polar studies (the arctic haze layer, sea and land ice, polar cyclones, the Antarctic ozone hole), mid-latitude studies (crop moisture, polluted boundary layers, severe convective storms, ocean currents and eddies, ocean productivity), subtropical studies (dry-land crop yields, ocean wind stress, hurricane structure), and equatorial studies (equatorial ocean currents, rain forest heat and moisture fluxes).

As with any other instrument platform-land, ship, or spacecraft-there are physical limitations on the capability of research aircraft. Constraints in such areas as altitude, range, endurance, and payload capacity are continually being removed as more advanced aircraft are made available to the scientific community.

Institutional factors have also influenced, and occasionally limited, the development of airborne science. The provision of aircraft resources to the scientific community involves a unique and complex form of research funding with inherent limitations.

1.2 New Directions in Geoscience

Recently the International Council of Scientific Unions endorsed a global research effort known as the International Geosphere Biosphere Program (IGBP), in which several nations will provide major research elements as contributions to an international assessment of Earth's state-of-health and habitability. Observations are an essential part of the IGBP, and airborne sensors have an integral role in these observations. Some of the primary airborne observational needs identified by the IGBP and related documents include:

- Continuing, long-term observations of parameters that may be indicators of change in global climate, including global sea level, volume and change of land and sea ice, surface temperatures, cloud types and heights, regional and global albedos, and the vertical structure of the atmosphere and oceans
- Climate-scale oceanic and atmospheric circulation patterns

- Basin scale productivity and global carbon flux for the world's oceans
- Vertical distribution of the rate of upper ocean heating
- Weather and severe storms
- Air chemistry process studies
- Definition of extent and monitoring of changes in distribution of selected ecosystems
- Measurement of oceanic parameters such as current distributions, temperature, salinity, and productivity
- Continuing measurements of the chemical composition of the atmosphere to identify changes in abundance and in vertical and zonal profiles of specific trace gases
- Studies of atmospheric processes through repeated sampling of evolving atmospheric structures.

In 1987, the NASA Advisory Council's Earth Systems Science Committee published a report making future program recommendations to NASA, NOAA, and NSF. The report, "Earth Systems Science: A Program for Global Change," indicated that after the current era of dispersed Earth systems science research, "During the second era of research to follow (the mid-1990's and beyond), emphasis will shift to [an] integrated program of global measurements....," and that "NASA will require, for example, expanded capabilities to make measurements from non-space platforms, such as aircraft and surface stations, exploiting the latest technology." That the requirement placed upon airborne geoscience by NASA and other agencies will continue and expand in "integrated programs of global measurements" in the near future is a prediction recently substantiated by the leadership role assumed by scientific research aircraft in the Airborne Antarctic Ozone Experiment.

1.3 Report Overview

The future needs of the various disciplines of airborne geoscience are discussed in detail in the following sections. Section 2, "National and International Geoscience Programs Employing Aircraft," presents a compendium of recent, current, or planned geoscience programs utilizing research aircraft, thus providing an overview of the significant geoscience problems being addressed with current airborne techniques. It also highlights the utility and necessity of research aircraft in modern scientific studies. Existing research aircraft and facilities of the three major airborne science agencies are described in Section 3, "Current Capabilities and Usage of Research Aircraft." Sections 4 through 8 outline the scientific challenges facing the various geoscience disciplines over the next decade, and describe the airborne instrumentation and platform advances required to respond to these challenges. Section 9, "Interagency and Agency-User Considerations," addresses some of the programmatic problems facing the airborne geoscience community and suggests some improvements in the areas of facility access; communication and information exchange; and interagency sharing of facilities and developments. The final section, Section 10, summarizes recommendations derived from the instrumentation and platform needs discussed in the previous sections. These recommendations collectively form a plan by which the utilization of research aircraft will become more efficient and more scientifically productive.

The appendices to this report include a table of current airborne geoscience aircraft usage and a compendium of existing airborne platforms and instruments and their uses and characteristics.

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National and International Geoscience Programs Employing Research Aircraft

NUMEROUS COORDINATED national and international geoscience research programs to be conducted during the late 1980s and 1990s have aircraft campaigns planned or proposed as a major constituent. In some cases, the aircraft element is the centerpiece of the program; in others, aircraft observations supplement data from satellite-, ground-, or ship-based sensors. Some of these programs have long-standing histories and are fundamental to the operational or research missions of the supporting agency, such as NOAA's hurricane research program and the various sensor development and calibration activities of NASA, NOAA, NSF. Many focus research towards the series of scientific problems collectively referred to as global change.

Although a tendency exists to portray the planned national and international programs that address problems of global change as primarily dependent upon the availability of satellites and satellite data, ground-based and airborne research will be indispensable. This section presents brief discussions of several planned, ongoing, or recently completed national and international programs in which aircraft have contributed significantly or will play a major role as platforms for basic research, data gathering, and sensor development.

The past use of aircraft for basic research has been impressive; the planned use of aircraft as an integral element in future programs is even more so. The following list of representative programs demonstrates the multidisciplinary/multiagency nature and scope of airborne geoscience. This list is not meant to be a complete documentation of all recent and upcoming scientific programs which utilize aircraft, but rather is intended to provide examples of major airborne research efforts in the various geoscience disciplines discussed in this report.

Joint Global Ocean Flux Study (JGOFS). This international program is targeted towards the determination, understanding, and prediction of the global fluxes of carbon and associated biogenic elements in the oceans and related exchanges with the sea-floor, atmosphere, and continental margins. A key platform for the required ocean basin scale observations is NASA's P-3 aircraft, which supports observations of ocean color and laser-stimulated fluorescence. Both of these measurements can be used to infer the amount of active phytoplankton in the upper ocean and their rate of photosynthesis and carbon uptake. Flight lines will be flown across the North Atlantic and meridionally in spring 1989; ancillary data collected from the aircraft will include sea-surface temperature, vertical temperature profiles, and solar radiation fluxes. In the United States, JGOFS is supported primarily by NSF and NASA, and there are national committees in Federal Republic of Germany, Great Britain, France, The Netherlands, Canada, and Japan.

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World Ocean Circulation Experiment (WOCE). This program will make a comprehensive survey of the world oceans to permit prediction of the ocean response and feedback to changes in the atmosphere on time scales of decades and longer. NSF is the lead agency.

Tropical Ocean and Global Atmosphere (TOGA). The scientific objectives of TOGA are to determine the extent to which the variability of the tropical oceans and related atmospheric circulation patterns are predictable on time scales of weeks to years, to understand the operative mechanisms therein, and to develop coupled atmosphere-ocean models for climate prediction. NSF and NOAA are the U.S. sponsors of TOGA.

Airborne Antarctic Ozone Experiment (AAOE). The flight measurements program of this experiment to gather data on the Antarctic ozone hole was completed in the fall of 1987. The experiment, sponsored primarily by NASA with substantial NOAA, NSF, and university participation, yielded dramatic evidence relating the abundance of chlorofluorocarbons to the destruction of ozone in the Antarctic stratosphere. The NASA ER-2 and DC-8 carried a combined payload of 21 instruments (*in-situ* sensors, sample collectors, and active and passive remote sensors) selected for their ability to answer specific questions regarding the hole's origin. The aircraft measurements were coordinated with satellite, balloon, and ground-based observations. A similar program for the Arctic is planned for January and February 1989.

Global Tropospheric Chemistry Program (GTCP). The primary goals of the GTCP are to measure and understand the basic chemical cycles in the troposphere and to predict changes in these cycles over the next century. Particular emphasis will be on changes affecting oxidizing capacity and radiative properties of the atmosphere and on the atmospheric component of the biogeochemical cycles. In order to accomplish these goals, field programs using large, long-range aircraft will be necessary. Because of the bulk of chemical instrumentation and the global scale of the program, aircraft with large payload capacities and long ranges are required. This program is currently sponsored by NSF, NASA, and NOAA.

Air/Sea Interactions: The Growing Role of Airborne Geoscience

As stated in "A Unified Plan for Ocean Sciences" (NSF, 1987): "Use of scientific aircraft for remote sensing of sea surface and air/sea fluxes has become increasingly important in recent years. Aircraft measurements in conjunction with coastal oceanography experiments are now common for production of maps of wind stress, sea surface temperature, and subsurface temperature (using expendable bathythermographs). Development of geodetic receivers and laser altimeters has increased the utility of these aircraft measurements, as has development of aircraft-mounted passive and active radiometers and radars. In the future, aircraft surveys of dynamic features will be possible, resulting in truly synoptic data at meso- to large scales, and WOCE and TOGA will require extensive measurements of air/sea fluxes, in part to improve our understanding and parameterization of these processes."

International Satellite Cloud Climatology Project (ISCCP). The long-term objective of ISCCP is to provide a global data set on the interactions of clouds and radiation, with applications to climate models. Aircraft used during the first field program associated with the First ISCCP Regional Experiment (FIRE) included NCAR's King Air, Sabreliner, and Electra; NASA's ER-2 and DC-8; a NOAA P-3; the University of Washington's C-131; a U.S. Air Force B-52, NKC-135, and Learjet; and a U.S. Navy Queen Air. A second series of flights is scheduled for 1990. The ISCCP is sponsored by the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU).

International Satellite Land Surface Climatology Project (ISLSCP). The goals of ISLSCP are to better understand the energy exchange between the surface of the Earth and the atmosphere and to measure the effects that changes in land-surface conditions have on these energy-exchange processes. The First ISLSCP Field Experiment (FIFE) was conducted over Kansas in 1987, using NASA's U-2, C-130, and a helicopter; King Airs from NCAR and the University of Wyoming; NOAA's Aerocommander; and a Twin Otter from Canada's National Aeronautical Establishment. ISLSCP is sponsored by the WMO and ICSU. Primary funding is from NASA, with support from NSF and NOAA.

Amazon Boundary Layer Experiment/ Amazon Ground Experiment (ABLE/AGE). The main objective of this NASA-sponsored multidisciplinary effort was to measure on a regional scale the gas fluxes between the biosphere and the atmosphere. Field efforts in the 1985 dry season and 1987 wet season included *in-situ* ground sampling, *in-situ* atmospheric sampling, and aircraft remote sensing. The aircraft measurements were obtained using the Electra from the Goddard Space Flight Center.

Biospheric Monitoring and Disease Prediction (BMDP). The goal of this program is to demonstrate how NASA-derived technologies can be used to study and model the environmental variables that influence the prevalence and distribution of vector-borne diseases. The NASA ER-2, DC-8, and C-130 are being used to obtain data and to evaluate the utility of new sensors. The data gathered by these sensors are currently being used in conjunction with satellite and *in-situ* observations.

Stormscale Operational and Research Meteorology (STORM). The key scientific issues to be addressed in STORM involve scale interactions and the production of precipitation; the development of cumulus convection and mesoscale (10-500 km) convective systems; and the effects of mesoscale fluxes of energy, moisture, and momentum on synoptic systems and climatic variability. NOAA, NSF, and NASA are participants in STORM.

Processing of Emissions by Clouds and Precipitation (PRECP). The goal of the PRECP program is to quantify chemical wet deposition as a function of air pollution, geographic location, and relevant atmospheric processes. PRECP is a national laboratory research program funded by the Department of Energy (DoE) as part of the National Acid Precipitation Assessment Program (NAPAP). The 1988 PRECP field experiment included the use of the Pacific Northwest Laboratory G-I aircraft, a NOAA P-3, and the NCAR Sabreliner.

Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA). The goals of the ERICA program, which will be conducted in the winter of 1988-89, are to develop

an understanding of processes leading to explosive marine cyclones and to identify variables useful for cyclone prediction. Three P-3s, two from NOAA and one from NRL, will be used, as will several Air Force WC-130s, and NCAR's Electra and Sabreliner. Primary funding is from ONR, NASA, NSF, and NOAA.

Genesis of Atlantic Lows Experiment (GALE). The GALE program, conducted in 1986, was a major atmospheric research experiment in which aircraft were the primary data-gathering platforms. This NSF-sponsored project was designed to study the rapid intensification of east-coast snow storms. These dangerous storms, which threaten some of the nation's largest cities, have proven to be very difficult to predict. Aircraft from NOAA, NCAR, NASA, and the university community joined forces to gather mesoscale and synoptic-scale data from the depths of the ocean through the entire troposphere, as well as from upper levels of the ocean. Using these data, scientists expect to improve numerical models, providing a basis for more accurate weather predictions.

Equatorial Mesoscale Experiment (EMEX). During the austral summer, convective activity in the area immediately north of Australia provides an enormous source of heat energy to the atmosphere. This energy is released into the atmosphere as water vapor from the tropical oceans. Heating occurs when the vapor converts to liquid water in the form of extensive cloud clusters. The main objective of the EMEX project was to determine the horizontal and vertical heating profiles of the atmosphere from this process. The NCAR Electra flew at low levels and measured moisture fluxes into the system; an Australian CSIRO F-27 measured cloud physics and state parameters at mid-levels; and a NOAA P-3 measured similar parameters and wind fields near the freezing level using an airborne Doppler radar. The data obtained in the experiment are crucial to the development of realistic numerical models of global circulations. In turn, these models will provide scientists with tools to study and predict climate patterns.

Program for International Polar Ocean Research (PIPOR). The objectives of this program are to use data from the European Space Agency Remote Sensing Satellite (ERS-1) to study air-sea-ice interaction and to demonstrate operational applications of sea-ice microwave data in ice-covered waters. It involves investigators from Europe, the United States, and Canada and will address research problems in both the Arctic and the Antarctic. A series of aircraft flights will be required before and during the ERS-1 mission, in order to make measurements needed for the development and validation of techniques for interpreting the ERS-1 data and to acquire ancillary data to complement those from the satellite.

Stratosphere-Troposphere Exchange Program (STEP). The main STEP objectives were to measure the rates and mechanisms of transfer of mass, trace gases, and aerosols between the upper troposphere and the stratosphere, and to investigate and explain the extreme dryness of the stratosphere. The STEP flights, carried out by a NASA ER-2, began in 1986 after 3 years of instrument-package development. The ER-2 flew an array of meteorological, trace-gas, particulate, and radiation sensors to and into transient targets of interest over the Micronesian region north of Australia, observing transfer mechanisms in and around tropopause folds and cumulonimbus anvils. The STEP data have proved to be of great value in the identification of the mechanisms by which natural and anthropogenic chemicals move from their sources into the stratosphere.

NASA DMSP SSM/I Sea-Ice Validation Program. A coordinated series of SSM/I aircraft underflights over portions of the Beaufort, Bering, and Chukchi seas was completed in March 1988 with NASA's DC-8 Airborne Laboratory and two Navy research aircraft. The primary sensors on board the three aircraft were high-resolution, multifrequency active and passive microwave instruments. The overall goal of this mission was to acquire coincident aircraft and satellite data in different regions of the Arctic for the purpose of assessing the accuracy of SSM/I-derived sea-ice parameters. A secondary objective was to acquire the requisite data to determine the potential of the new 85-GHz SSM/I channels for polar research and to develop sea-ice algorithms for interpreting SAR data that will be acquired from ERS-1 at NASA's Alaska SAR Facility (ASF) at the University of Alaska, Fairbanks.

The experiments listed above provide a general indication of the multiagency, multidisciplinary nature of airborne geoscience as we move into an era focused on global change issues. Airborne research programs also support a wide variety of less heralded, smaller-scale studies, including annual hurricane reconnaissance, ice patrols, and mapping tasks. To support the broad spectrum of science requirements, the three major agencies involved in airborne programs, NASA, NOAA, and NSF/NCAR, maintain fleets of instrumented aircraft at their flight facilities. Section 3 will provide detailed information about these facilities and the aircraft they support.

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Current Research Aircraft Capabilities and Uses

THIS SECTION OFFERS a survey of the capabilities of existing airborne geoscience research facilities maintained by U.S. Federal agencies. Specific details of aircraft and instrument performance characteristics can be found in Appendix B.

Airborne research activities for the Earth sciences in the U.S. Government are concentrated in three agencies: NASA, NOAA, and NSF/NCAR. (Elements of the Department of Defense are also involved, but most of the broad, multidisciplinary and interagency airborne geoscience activities are funded and administered through these three agencies.) The NASA, NOAA, and NSF/NCAR airborne research activities have distinctive foci that are driven by each agency's research mission. In support of the programs of their Environmental Research Laboratories (and related research by the university community), NOAA research focuses on the atmosphere and oceans. NCAR's primary mission involves providing airborne measurement support to the NSF/NCAR scientific community, consisting of NSF grantees (generally university scientists) and NCAR research scientists. NCAR aircraft typically support atmospheric or oceanic research programs. NASA research activities assume the broadest scope, including all the Earth sciences, and other discipline studies consistent with NASA's mission, such as astronomy and bioscience. In general, NASA airborne research support is tied closely to evolving spaceborne observing systems.

A comprehensive listing of aircraft utilization for ongoing and planned scientific missions appears quarterly in the *Airborne Geoscience Newsletter*. The most recent table is republished here as Appendix A. Information on the characteristics, performance, and uses of the aircraft operated by the three agencies is provided in Appendix B.

The following discussion describes in general terms the airborne platforms operated by NASA, NCAR, and NOAA; their typical flight missions; and how investigators can request flight time.

3.1 NASA Research Aircraft

NASA now operates several scientific research aircraft at four field installations: Ames Research Center (ARC) (seven aircraft); Johnson Space Center (JSC) (one aircraft); Goddard Space Flight Center's (GSFC's) facility at Wallops Island, Virginia (five aircraft); and the Stennis Space Center in Mississippi (one aircraft). The aircraft operated by the major NASA aircraft facilities, ARC and Wallops Island, are described herein. Appendix B provides information on their performance characteristics, principal user accommodations, and sensors.

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3.1.1 Ames Research Center

The Ames Research Center's scientific research aircraft fleet consists of two ER-2s (replacing two U-2s that have been phased out), a DC-8, a C-130, a C-141 (dedicated to astronomy), and a Learjet. The DC-8 was acquired in 1986 as a replacement for the CV-990 lost in an accident in 1985, and operates in the same capacity as its predecessor and with similar investigator accommodations. In 1987, the DC-8 was modified for, and participated in, the Antarctic Airborne Ozone Experiment. The DC-8 then returned to ARC for the installation of the new Jet Propulsion Laboratory (JPL) Synthetic Aperture Radar (SAR). Data acquisition flights with SAR took place in early 1988, followed by further modifications to install up-looking and nadir viewports, exterior mount points, and other support facilities.

The DC-8 does not fly with a fixed complement of sensors. Most missions are planned in blocks of time with instruments brought in and out for each mission by the investigators. The C-130 flies with a fixed sensor package and has space allocated for investigator-supplied instrumentation. The ER-2s employ a pallet system for various sensor combinations. Some of these sensors are made available by the facility manager, but most are furnished by the principal investigators (PIs).

The ARC aircraft fleet supports all the Earth science disciplines of interest to this report. The DC-8 is a multidisciplinary laboratory used extensively for atmospheric chemistry, atmospheric dynamics, and land processes, with some support for oceans and the cryosphere. The C-130 is used almost exclusively for land processes research. The ER-2s are used primarily for land processes and atmospheric investigations.

A flight-request system facilitates ARC's process of planning its annual flight programs. Flight planning cycles are on a fiscal-year basis and coincide with the planning cycles of the research programs in the various disciplines. Scientific tasks are described in NASA Research and Technology Operating Plans (RTOPs), which are reviewed and, if approved, funded by NASA Headquarters. Airborne support required by these tasks is detailed in a flight request, which includes requested flying hours, instruments required, location, timing, and flight parameters. To be accepted, a flight request must relate to an approved scientific task and must be within the capabilities of the facility.

A PI, usually a NASA-funded scientist, is identified for each flight request; typically, however, several co-investigators from the broader user community are also brought in. Requests for flight support from entities outside of NASA are handled on a time-available and cost-reimbursement basis.

3.1.2 Goddard Space Flight Center

NASA's Goddard Space Flight Center operates five aircraft from its Wallops Flight Facility (WFF) near Chincoteague, VA, for NASA Earth science programs. Aircraft include a Lockheed Electra, a Lockheed P-3, a Short Skyvan, a Rockwell Sabreliner, and a Bell UH-1B helicopter. Like ARC, the WFF aircraft facility supports atmospheric, land, and oceanic investigations. The Electra is used mostly for atmospheric chemistry studies, the P-3 for ocean studies, the Skyvan for land processes and instrument development, and the UH-1B helicopter primarily for land processes. While most of the sensors flown on WFF aircraft are furnished by the investigators, the cameras, airborne oceanographic lidar, surface-contour radar, and navigation and environmental measurement systems are available at the facility. Cooperative investigations using the above systems are possible, if approved by the appropriate NASA PIs.

To obtain use of WFF aircraft, a letter of request indicating scientific objectives, flight hours, instruments, flight location, and schedule initiates the approval and planning process. Approval of the flight request is based on its relationship to NASA's scientific interests and the facility capability. Small projects may be initiated and conducted in time periods as short as 1 month, while larger projects may require up to a year to plan. Flight support is generally provided on a cost-reimbursement basis.

3.2 NSF/NCAR Research Aircraft

NCAR offers a wide range of aircraft capabilities and instruments in support of atmospheric research programs sponsored by NSF. These facilities are maintained by the NCAR Research Aircraft Facility (RAF) at the Jefferson County Airport in Broomfield, Colorado. Aircraft available include a Lockheed Electra, a Beech King Air 200, and a Rockwell Sabreliner. RAF is currently developing plans to add a mid-sized jet aircraft (i.e., a Gulfstream G-IV-class) to its fleet during the FY 90-92 time period as a replacement for the Sabreliner. Current aircraft performance, uses, and sensor listings can be found in Appendix B.

Generally, all RAF aircraft are equipped with sensors to measure meteorological and chemical state parameters, including temperature, pressure, dew point, ozone, and winds. In addition, a large variety of other RAF instruments can be selected by users for a particular project. Users can also supply their own special instrumentation.

All RAF aircraft are equipped with computer-controlled data-logging and display systems that record data and provide real-time graphic and tabular output during flight. Considerable freedom is permitted in mounting user-supplied instrumentation and in interfacing it to RAF aircraft data systems. Data tapes generated during research flights are processed by the RAF Computing Group to produce edited, quality-assured data tapes containing measured and derived parameters in a standard format. RAF also has the capability to process raw data tapes in the field in a "quick-look" mode, using onsite hardware and software to provide both the investigator and RAF personnel the opportunity to examine data in near-real time.

An RAF project leader serves as the primary interface with the user scientist. The project leader assists in project planning, operational mission design, quality control for sensor and data system performance, data processing, and final data delivery. RAF pilots work with investigators through the RAF project leader to plan missions, to obtain FAA clearances, and to meet any special requirements concerning flight operations.

Requests from potential users for RAF support are reviewed twice yearly by the RAF Advisory Panel, which advises the NCAR Atmospheric Technology Division (ATD) Director on support allocations. Based on its assessment of the scientific merit of the request for support, as well as of the feasibility of the operational and instrumentation plan and the plan for data processing, the Panel recommends to the ATD Director whether or not to support the project. A major portion of NCAR's available flight support is base-funded by the NSF and is therefore reserved for use in NSF-supported university and NCAR scientific programs. Accordingly, such programs are not burdened with the costs of any NCAR flight support that is allocated to them.

Requests for flight support from entities outside of NSF are handled on a time-available and cost-reimbursement basis, contingent upon favorable reviews by the RAF Advisory Panel and the ATD Director.

3.3 NOAA Research Aircraft

NOAA operates 12 fixed- and rotary-wing aircraft through its Office of Aircraft Operations (OAO) at Miami International Airport. Four of these aircraft are of interest to this study, three of which (two WP-3D Orions and one King Air) are specifically dedicated as flying laboratories for measurement and investigation of atmospheric and ocean phenomena, and a fourth, a Cessna Citation, which is primarily used for photo-mapping.

Recent OAO WP-3D equipment upgrades include new flight data acquisition systems, Doppler radar systems, a new gust-probe system for turbulent flux measurements, and a voice satellite link. OAO has worked closely with the NOAA Hurricane Research Division to improve onboard real-time data analysis and transmission for the WP-3D's. Since the acquisition of the King Air aircraft by NOAA, a suite of air-chemistry instruments has been installed, primarily in support of acid rain research. Specific information on these systems is contained in Appendix B. The latest information on NOAA/OAO aircraft upgrades is published quarterly in the *Airborne Geoscience Newsletter*.

The Cessna Citation is a high-altitude (43,000 feet) aircraft with limited payload capability. Used primarily for aerial photography in support of NOAA's marine and aeronautical charting divisions, the Citation can be, and has been, converted for use as a high-altitude dropwindsonde aircraft.

NOAA aircraft are available on a cost reimbursement basis for any agency that is conducting an appropriate project. Base-funded flight time is available on the P-3s for NOAA or NOAA-affiliated programs; however, larger programs typically include major participation from the university community and other agencies. Applications for base-funded flight time are submitted by NOAA PIs through their parent division to the NOAA Aircraft Allocation Council (NAAC) by March of each year for flight time allotments in the following fiscal year. Each major division within NOAA is responsible for scientific review and screening of the requests before forwarding them to the NAAC.

Requests for cost-reimbursed flight time can be sent directly to the Director of OAO for a feasibility and cost analysis. Costs vary according to staging location, duration of deployments, and reconfiguration requirements. Expendables are the responsibility of the user. No specific deadlines exist for aircraft requests for reimbursable projects; however, lead times are required for scheduling, planning, and instrumentation changes. Scheduling conflicts are resolved by the NAAC.

3.4 Other Agencies

The Division of Polar Programs (DPP) of NSF operates a fleet of seven LC-130 Hercules ski-equipped airplanes in support of polar research. One of these aircraft had been used to systematically photograph portions of Antarctica for cartographic and other purposes; it had also been used to map the ice surface and bedrock topography of both Greenland and Antarctica using ice-penetrating radar. Unfortunately, this aircraft, the only one of the fleet equipped with camera ports, ice-radar antenna mounts, and a digital data acquisition system, was lost in an accident in 1987. DPP scheduled the use of this airplane for both logistic and operational purposes; it was operated by the U.S. Navy.

The USGS has been using aircraft for aerial mapping and aeromagnetic surveys for many years. Almost all of this work has been performed by commercial contractors. However, USGS does maintain an aircraft for research and development of magnetic and electromagnetic instrumentation. At present, the USGS aircraft is a Fairchild Pilatus Porter PC6,

a high-wing turboprop aircraft capable of cruising at suitably low speeds (100 knots) at low altitudes (100 meters). Other USGS airborne science activities, often employing aircraft from other agencies, include gamma-ray spectrometry and interpretation of remote-sensing data.

Within DoD, several aircraft are being used by the Air Force Geophysics Laboratory and the Naval Oceanographic Command for military research and development activities. These facilities are normally not available to the broad geoscience community and thus will not be described in detail here.

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Atmospheric Science: Scientific Challenges and Airborne Observational Needs

RESEARCH AIRCRAFT have a history of significant contributions to the understanding of atmospheric phenomena. Given the increasing call for improvements in short- to medium-range severe weather forecasting, and for better understanding of acid rain transport and local and global atmosphere composition, the use of aircraft in atmospheric studies is expected to increase. Complete studies of atmospheric phenomena are inherently interdisciplinary, but for the purpose of discussion, the following paragraphs illustrate the kinds of specialized research necessary to meet basic objectives in atmospheric science.

4.1 Climate

4.1.1 The Scientific Challenge

Climate, by definition, is a long-term aggregation of weather patterns. Consequently, climatic studies cover a broad range of time scales from interannual to decadal and longer. To some degree, different mechanisms are involved with the climate changes at the various scales.

For example, changes in the amount and location of energy transfer from the oceans to the atmosphere appears to be critical to interannual variations in climate. During the major "El Niño" event of 1982-83, a locus of convective activity, which provides the largest single wintertime source of atmospheric energy, moved thousands of miles eastward from its normal location north of Australia to the south of Hawaii. The resulting change in climate patterns was dramatic: uncharacteristically high typhoon activity in Tahiti; a 3,000-percent increase in rainfall in eastern South America; the most severe drought in Australian history; winter storms, which normally would have tracked into Alaska, pounding the coast of southern California; and tremendous increases in snowfall causing months of severe flooding in the western United States during the snow-melt period.

The first step in predicting such climatic changes is reaching a better understanding of the mechanisms involved in climate processes. Research aircraft have been directly involved in numerous process studies concerned with the transfer of radiative energy to the atmosphere and oceans, the transfer of latent energy in the form of moisture vapor from the oceans to the atmosphere, the reaction of the atmosphere to the release of this latent energy, and the reaction of the ocean to changes in long-term wind patterns by measuring subsurface temperature profiles.

Research aircraft have also played an important role in process studies for decadal climate changes. As stand-alone platforms and in concert with ground- and ship-based installations, aircraft have enabled the measurement of concentrations and fluxes of

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atmospheric gases like CO_2, ozone, Freons, methane, and nitrous oxide, which play a key role in long-term global temperature changes known as the "greenhouse effect." These airborne studies have extended from the stratosphere to the ocean surface and from the Arctic to the tropics; the data they have provided have proven to be invaluable for global atmospheric chemistry models.

4.1.2 Airborne Observational Needs

Climate programs require aircraft data in a variety of atmospheric disciplines, such as boundary-layer processes, radiative processes, atmospheric dynamics, and atmospheric chemistry. Therefore, the platform and instrumentation requirements for each of these disciplines are discussed separately in the subsections that follow.

4.2 Atmospheric Chemistry

In the past 40 years, atmospheric chemistry studies have evolved from simple field measurements, such as an examination of the airborne pollutants that caused the cracking of rubber products in Los Angeles, to regional studies employing extensive numerical models and involving detailed chemical measurements from aircraft. During this time, awareness of the actual and potential impact of anthropogenic emissions on the Earth's atmosphere has expanded. Earlier concerns over the effects of supersonic transport exhaust and Freons on the chemistry of the stratosphere, coupled with the more recent documented evidence of acid deposition and the discovery of the Antarctic ozone hole, have focused attention on atmospheric chemistry. To respond to these problems the scale of atmospheric chemistry studies has increased to include regional and global investigations.

4.2.1 Tropospheric Chemistry: The Scientific Challenge

As in all of the atmospheric sciences, the scale of tropospheric chemistry has broadened, and aircraft have become an integral tool for field research. Programs such as PRECP and the Airborne Antarctic Ozone Experiment would be impossible without aircraft to conduct long-range tropospheric and stratospheric sampling (see Section 2 for details of these and other programs.) Major tropospheric chemistry field projects typically contain an integral aircraft component.

The composition of the Earth's atmosphere changes dramatically as one proceeds from the surface to several hundred meters above the surface, and additional changes are measured through the boundary layer into the free troposphere and beyond. Aircraft-based measurements are necessary to understand a three-dimensional composition of the atmosphere, since surface measurements for reactive species are not representative of those aloft. Three-dimensional knowledge of the atmospheric chemical composition is essential for the formulation and validation of numerical models of the atmosphere.

Tropospheric chemistry will place increased emphasis on airborne sampling in the foreseeable future. Aircraft platforms have capabilities to reach remote areas of relatively unpolluted air and can profile these regions to provide a basis for an understanding of the atmospheric chemical processes taking place. Remote-sensing improvements will eventually provide near-global measurements of some chemical species, but these developments are a decade or more away, will primarily serve to augment *in-situ* measurements, and will never match the spatial resolution and variety of species that can be measured *in situ*.

4.2.2 Tropospheric Chemistry: Airborne Observational Needs

The development of airborne atmospheric chemistry sensors can be viewed as second- and third-generation advancements from the initial ground-based measurement systems. In the past, development has stopped with the second generation, wherein the instrumentation is adapted to the aircraft in a manner simply designed to ensure successful measurement. To make an instrument-aircraft marriage complete, however, a third-generation development, fully integrating the instrument and aircraft systems, must evolve. In this third-generation development, improvements in sensitivity, response time, sample inlets for aircraft, and miniaturization must be implemented. These improvements form the core of the needs described below.

Enhanced Chemical-Sensor Sensitivity and Response Time. Because the concentrations of most species decreases above the boundary layer, improvements in sensitivity are necessary to obtain reliable measurements. Response times of 1 second or better are needed for flux measurements. This response is substantially faster than is typically obtainable with most current chemical instruments.

Development of Improved Inlet Systems for use with Analytical Instrumentation. Techniques to measure various radical species are being developed in the laboratory and could be available for aircraft deployment within the next several years. Since these radical species have subsecond lifetimes, the proper design of inlet systems will be crucial. Research on inlet systems has not had significant emphasis and must be stressed so that the interface between the aircraft and measurement device is improved and more completely characterized.

Miniaturization. As described above, the final stage of the third generation of aircraft instrumentation development is miniaturization. Although planetary exploration programs have lead to the development of spaceborne chemical analytical instruments in shoebox-size packages, this degree of ultra-miniaturization is not practical for airborne research instruments. However, corollary efforts need to be made to reduce the size of chemical analytical instruments for better integration into the aircraft environment. The result will be to reduce the requirements on the aircraft power and air-conditioning systems. The reductions in weight and size will permit the use of smaller aircraft or larger instrument packages.

Balloons and Safe-Sonde Profilers. Improvements in chemical-measurement instrumentation alone is insufficient to improve our understanding of chemical transports and dispersion. Accurate data on air-mass movement is also required for computer model input. Both constant-level balloons and safe-sonde profilers will be necessary. The present development of these items must be continued.

Large, High-Capacity, Long-Range Aircraft. Atmospheric chemical sampling requires aircraft with large interior space, ample power, high-capacity air-conditioning, and flexibility in exterior mounting points. The aircraft also must have performance characteristics that will permit sampling from the lower part of the boundary layer to the upper troposphere with adequate range to reach remote areas over the ocean.

4.2.3 Stratospheric Chemistry: The Scientific Challenge

Many of the challenges and needs described above for tropospheric chemistry also apply to stratospheric chemistry. Obviously,

however, stratospheric chemistry requires measurements at much higher altitudes. In the past the majority of stratospheric chemical measurements have been made from balloons. These have the advantage of a much higher altitude range than aircraft. However, there are significant disadvantages to balloons, including: (1) launch facilities (for integrated, sophisticated packages) are restricted to a few locations worldwide; (2) launch opportunities are highly restricted by local weather and stratospheric winds; (3) balloons are unable to repeatedly access moving, changing atmospheric features (such as tropopause folds, jets, vortices, clouds, and concentration maxima and minima); and (4) the risk of payload loss significantly exceeds that for aircraft. Because of these disadvantages, considerable effort has been devoted to developing atmospheric research instrumentation for high-altitude aircraft. Instruments to measure ozone, carbon monoxide, total reactive odd nitrogen, nitric oxide, nitrous oxide, water vapor, chlorine monoxide, bromine monoxide, whole-air samples (post-flight analyzed for long-lived tracers such as methane, nitrous oxide, carbon dioxide, and Freons), aerosol size and composition, cloud particles, radiation, and various meteorological phenomena were developed for and successfully flown in the Stratosphere-Troposphere Exchange Project (STEP) and the Airborne Antarctic Ozone Experiment (see Figure 4-1).

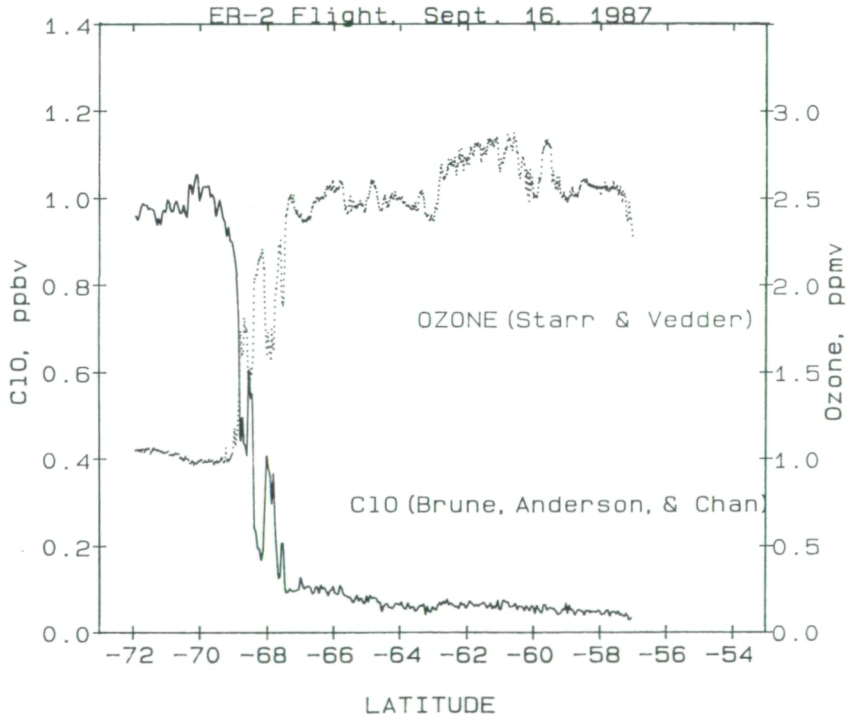

Figure 4-1. Antarctic Ozone Measurements

Measurements by the NASA ER-2 at 64,000 feet over the Antarctic showed the dramatic inverse correlation between chlorine monoxide and ozone upon entering the "ozone hole." This was some of the most compelling evidence that perturbed chlorine chemistry is at least partially responsible for the occurrence of the hole.

4.2.4 Stratospheric Chemistry: Airborne Observational Needs

Mid-Sized, Long-Range, High-Altitude Jet Aircraft (see 4.6 below).

Ultra-High-Altitude Subsonic Aircraft (see 4.6 below).

4.3 *Atmospheric Dynamics*

Atmospheric weather systems have a profound effect on day-to-day human activities. Unfortunately, the timing and location of some of the most severe events (such as tornadoes, microbursts, flash floods, hailstorms, and heavy ice and snow storms) are poorly forecasted because of inadequate observations and inadequate understanding of the physical processes that lead to these events. Aircraft observations and remote-sensing instruments, both airborne and ground-based, are currently the only practical means for obtaining *in-situ* measurements of atmospheric structure on which to base new conceptual and numerical models.

It is convenient to divide atmospheric dynamics into: 1) processes that occur near the Earth (in the atmospheric boundary layer), 2) weather systems that produce precipitation, 3) stratosphere-troposphere exchange processes, and 4) clear-air mesoscale circulations. The following paragraphs are so divided.

4.3.1 Atmospheric Boundary-Layer Processes: The Scientific Challenge

Sensible and latent energy fluxes at the Earth's surface and the transfer of energy and momentum through the planetary boundary layer affect synoptic and mesoscale phenomena on time scales ranging from less than 1 hour to many days. The importance of boundary-layer processes to the development of severe convection, the transport and diffusion of pollutants, and the development of horizontal and vertical circulations (e.g., sea-breeze circulations), is well known, as is the role of diurnal boundary-layer processes in the development of mesoscale phenomena such as low-level jets and mesoscale convective systems.

A detailed and accurate treatment of surface and boundary-layer fluxes will be essential for improvements in the models of mesoscale phenomena used in operational weather forecasting (see Figure 4-2). Simple one-layer models using bulk aerodynamic formulas, such as those which have been used for years in operational synoptic-scale forecasts, are not adequate to model and forecast properly many mesoscale features of interest.

4.3.2 Atmospheric Boundary-Layer Processes: Airborne Observational Needs

Improved Turbulence Sensors. Improved understanding of boundary-layer physical processes will result from the application of new *in-situ* measurement technology. Improved turbulence sensors, coupled with advanced temperature and humidity probes and faster-response chemical sensors, would lead to better quantification of turbulent fluxes of heat, moisture, trace gases, and chemical species into the atmosphere.

Improved Clear-Air Remote Sensors. Studies of clear-air phenomena could be easily made by a lidar mounted on a small aircraft. Such a platform would be useful in documenting the kinematic structure and evolution of a variety of small scale, clear-air, boundary-layer systems such as roll vortexes, thermals, dust devils, water spouts, thunderstorm gust fronts, and tornadic funnels.

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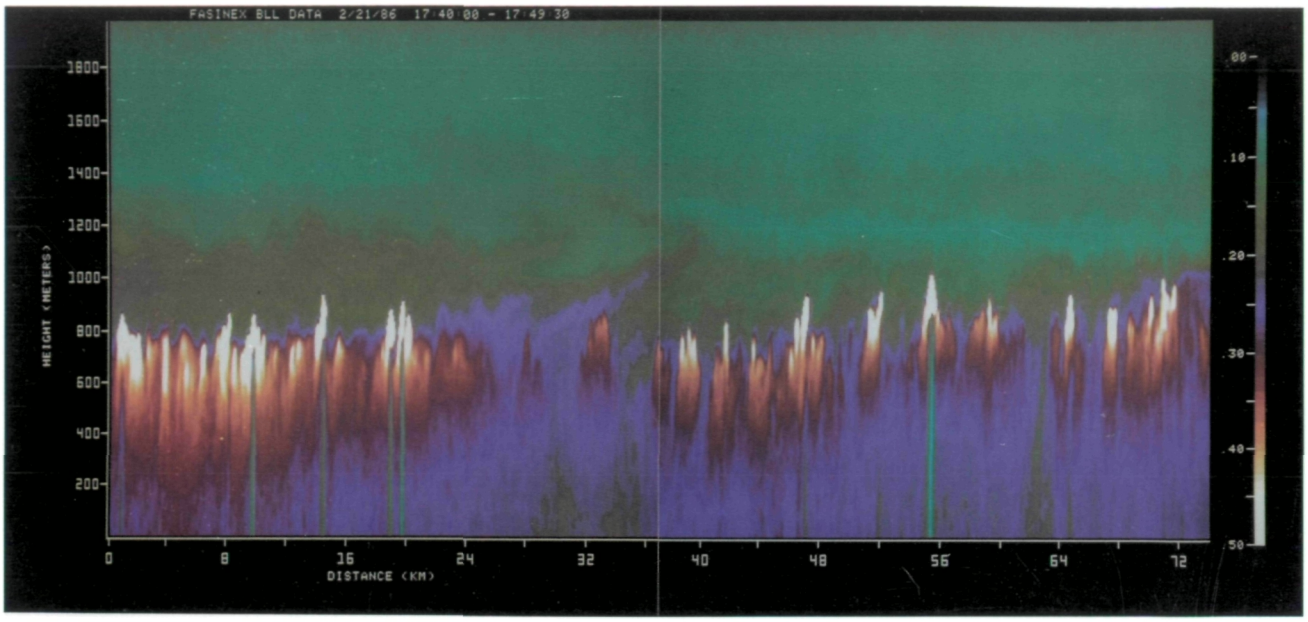

Figure 4-2. Lidar Observation of the Boundary Layer

The structure of the planetary boundary layer observed using a downward-looking airborne lidar. These measurements were made over the Atlantic Ocean during the Frontal Air-Sea Interactions Experiment (FASINEX) on February 21, 1987.

4.3.3 Weather System Dynamics: The Scientific Challenge

Mesoscale convective systems produce 80 percent of the growing season precipitation and nearly all of the tornadoes, flash floods, dangerous wind shears, and severe wind storms in the central United States. The majority of the systems are largely unforecasted by current operational weather prediction models because they occur on time and space scales smaller than those resolved by the models.

Cyclonic storms are important sources of precipitation and severe weather in the United States during winter and spring. Most of the clouds and precipitation in cyclonic systems are organized on the mesoscale, but the conventional synoptic observation network is too coarse to resolve these mesoscale motions. Aircraft, therefore, are important in measuring the phenomena contributing to the organization of this severe weather.

Hurricanes pose a serious threat to life and property for all U.S. coastal areas bordering the Atlantic Ocean and the Gulf of Mexico. Current studies of hurricane dynamics are expected to produce a significant increase in the predictability of storm tracks and intensity changes through improved numerical models (see Figure 4-3). High-density data from aircraft are critical both in the scientific study of these systems and in providing near-real-time data to forecasters.

Frontal circulations and related mesoscale phenomena also require specialized short-term experiments. Tropospheric fronts play major roles in extratropical cyclogenesis, interact strongly with jet stream systems, provide mechanisms for exchange of air and chemical trace constituents between the stratosphere and troposphere, and produce mesoscale vertical circulations responsible for a variety of mesoscale precipitation systems. Observations of the kinematic and thermodynamic

Hurricane Preparation Costs

Improvements in the confidence level for predicting hurricanes will have immediate economic benefits. On the average, the National Hurricane Center warns 300 nautical miles of coastline 18-24 hours in advance of an impending storm. However, the swath of damaging winds and tides caused by hurricanes is generally less than 100 nmi. Since it costs the public an estimated average of $155,000 per mile of coastline to prepare for a storm, hurricane preparation costs could be significantly reduced if average errors associated with landfall forecasts were decreased. High-density and near-real-time data from aircraft are a crucial part of this process.

structure of both dry fronts and fronts producing mesoscale precipitation are needed to address these questions. The only practical method for making these detailed observations over a long time period is with an aircraft.

The most important observational requirement for improved understanding of these mesoscale weather systems is the ability to carry out specialized, short-duration field experiments. In particular, there is a need to measure the three-dimensional structures of temperature, moisture, liquid water, winds, and cloud parameters on horizontal scales of approximately 500 km at a frequency of at least 1 per hour, with a horizontal and vertical resolution of at least 1.0 x 0.1 km, and following the system from genesis to dissipation. Future airborne platform and instrumentation requirements driven by these observational needs are described below.

4.3.4 Weather System Dynamics: Airborne Observational Needs

Mid-Sized, Long-Range, High-Altitude Jet Aircraft (see 4.6 below).

Long-Range, Storm-Penetrating Aircraft. Because the dynamic weather systems listed above have large areas of stratiform precipitation and embedded convective storms with severe weather (hail, tornadoes, wind shear, intense electrical activity), a storm-penetrating aircraft would need to be insulated against lightning strikes and be able to tolerate penetrations of regions of moderate graupel and icing. Improved navigational weather radar with turbulence detection capability would be needed to navigate the aircraft safely around strong convective storms. Given the long lifetimes of most atmospheric systems and the large areas they traverse, the ideal observation platform would be a long-range, storm-penetrating aircraft equipped with airborne Doppler radars, lidar, dropwindsondes, field mills, and microphysical instrumentation. Updated navigation systems that can reliably pinpoint the aircraft's position to within 100 m are essential if airborne Doppler radar data is to be combined with ground-based Doppler data to derive wind velocities.

New instrumentation required to achieve the goal of complete 3-dimensional coverage of the kinematic and thermodynamic state of weather systems is described in the following paragraphs.

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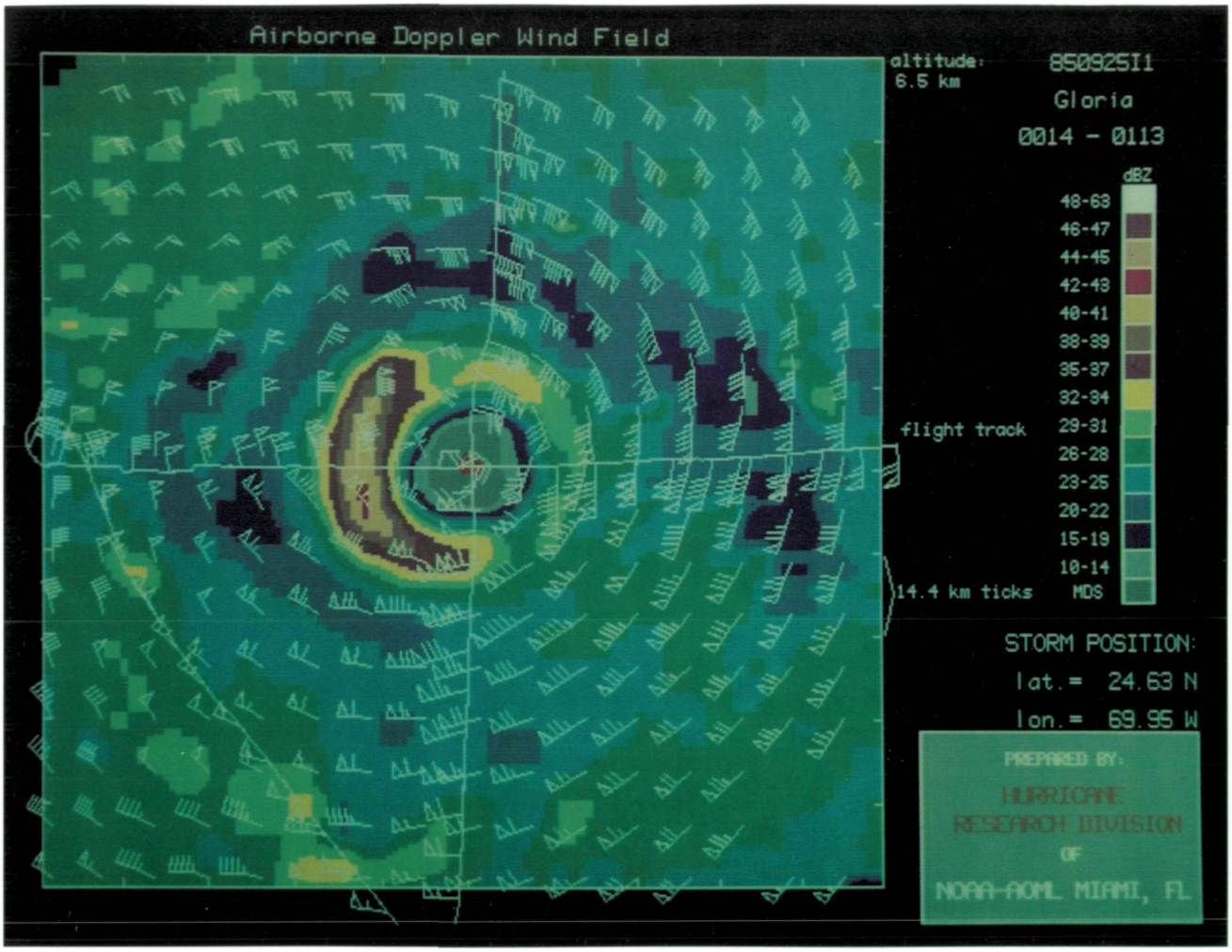

Figure 4-3. Radar Reflectivity and Doppler-Derived Winds in Hurricane Gloria

Tail radar reflectivity and airborne Doppler-derived winds at 6.5 km altitude in Hurricane Gloria at 0014-0113 UTC, September 25, 1985. The analysis covers a region 144 x 144 km, and the tick marks are 14.4 km apart. The reflectivity (dBZ) is color coded and the horizontal Doppler wind field (white wind barbs) are shown every 9 km. Superimposed over the reflectivity and Doppler wind field is the aircraft flight track (solid line) with flight-level winds (6.1-6.5 km) plotted at 1 min. intervals. The wind plotting convention is flag, 25 m/s; barb, 5 m/s; and half barb, 2.5 m/s. The storm center determined from flight-level observations is denoted by the hurricane symbol.

Airborne Doppler Radar. Ground-based multiple-Doppler radar systems have been used for many years by atmospheric scientists to study storm-scale velocity structures. The limited range of these systems led to the development of single-beam airborne Doppler radar systems that can be flown to the storm system of interest. However, these systems, two of which are currently installed on two NOAA P-3 aircraft, have limitations. With a single-beam system one can obtain only the radial motion component at any one time—an aircraft must fly an extended, L-shaped pattern around a storm in order to measure the 2- and 3-dimensional motions, thereby incurring potentially serious errors in the derived

motion field due to temporal changes in the storm dynamics. To help remedy this problem, the development of a dual-beam airborne Doppler radar system that can measure all three motion components during one straight flight track past a storm system is currently underway. This airborne system will be capable of mapping the detailed velocity structure of precipitating cloud systems at a rate of 50,000 to 70,000 square kilometers per hour. Such measurements will be highly useful to studies of mesoscale convective complexes and other storm systems. Development of dual-beam airborne Doppler radar systems should be continued as a high-priority effort.

Airborne Doppler Lidar. Since airborne Doppler radars of the type being developed use wavelengths that normally give useful signal return only from areas where precipitation is occurring, there is a need for other remote-sensing instruments that can obtain velocity measurements in clear air and non-precipitating clouds. This need can be filled by airborne Doppler lidar systems, which normally use a laser wavelength of approximately 10 micrometers. Such systems can measure air motions by detecting Doppler-shifted backscatter from aerosols and cloud droplets, and thus will serve as useful complementary sensors when used in conjunction with Doppler radar systems.

Safe Dropwindsondes. Currently, no system exists for making *in-situ* sounding measurements over land because of the size and weight of the sondes (sounders) used (the most widely used is the omega dropwindsonde system [ODW]). Studies of mesoscale weather systems would benefit substantially from the ability to deploy sondes from aircraft in data-sparse regions and to complement remote-sensing instrumentation. A lightweight, frangible sonde would be an ideal solution to this problem.

Airborne Radiometric Observations. Many weather systems have regions that are unsafe for aircraft penetration. Other regions, such as high-altitude regions, may be beyond the performance limits of the aircraft. Remote-sensing instrumentation is required if these regions are to be observed. For example, an airborne dual-channel microwave radiometer to measure path-integrated liquid water and water vapor as well as super-cooled water would greatly extend the ability to observe cloud parameters.

4.3.5 Stratosphere-Troposphere Exchange: The Scientific Challenge

Exchange of air between the stratosphere and troposphere has an important effect on the chemical composition of both regions. Distinctly different exchange mechanisms occur in different latitudes. In the tropics, penetrating cumulonimbus clouds and their associated cirrus anvils provide an important means of injecting tropospheric trace species into the stratosphere. In the mid-latitudes, tropopause folds associated with frontogenesis and the jet stream provide a major pathway by which stratospheric air returns to the troposphere.

Despite the global importance of stratosphere-troposphere exchange, the actual exchange events are highly localized, transient, and associated with developing meteorological structures, such as individual cumulonimbus clouds and tropopause folds. The latter, in turn, are associated with low-pressure troughs. Understanding and quantifying these exchange mechanisms requires measurements with fine temporal, horizontal, and vertical resolution, and the ability to access and repeatedly sample developing, moving atmospheric structures. Neither satellites nor balloons combine these capabilities, but aircraft provide them very well. Hence, the bulk of our detailed knowledge about stratosphere-

troposphere exchange processes has come from aircraft measurements. (See Figures 4-4 and 4-5.)

In mid-latitudes, tropospheric aircraft (e.g. King Air, Electra, CV-990) have documented the structure and composition of penetrating tropopause folds with both *in-situ* and remote (lidar) sensors, whereas stratospheric aircraft (U-2, ER-2) have measured associated wind, temperature, trace gas, and particulate structures above the jet-stream core. In the tropics, U-2 and ER-2 measurements have documented the difference between the hygropause (water vapor minimum) over Panama and that over Northern Australia, pointing to the latter as the preferred injection region. The tropical ER-2 measurements have also documented radiation fields and particle populations associated with clouds near the tropopause, thus shedding light on the dynamics and possible dehydration associated with these clouds.

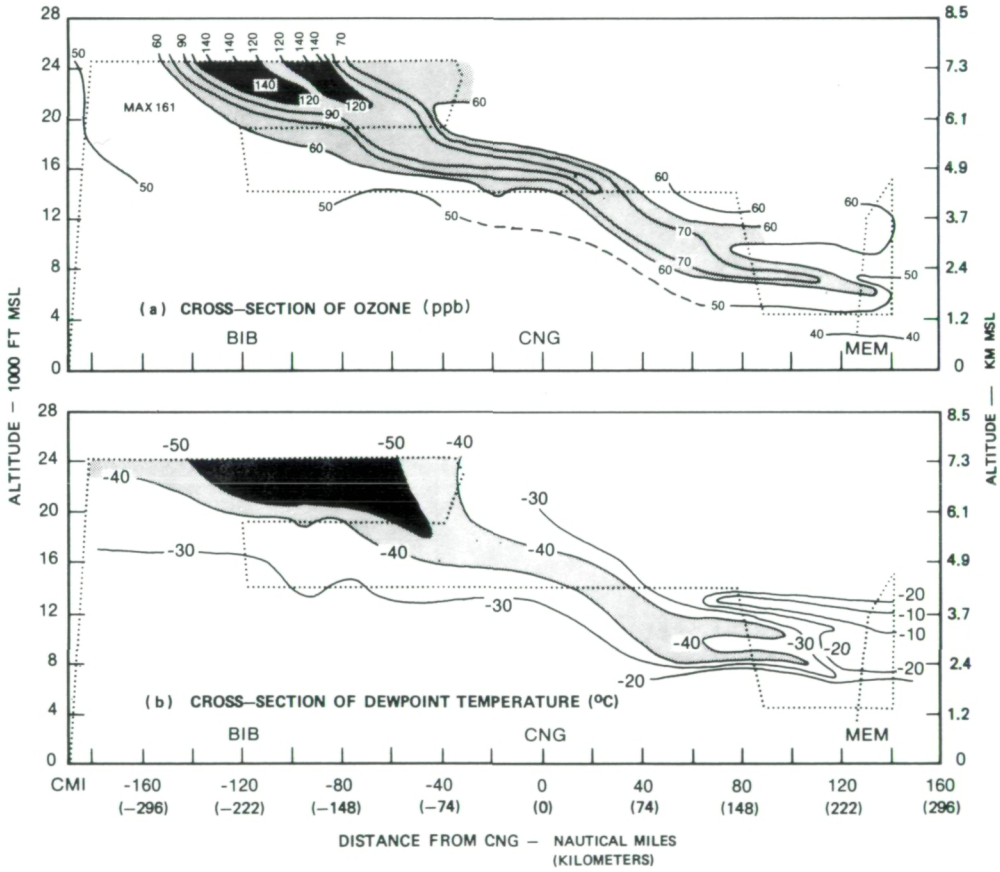

Figure 4-4. Tropopause Fold Observations Using Airborne **In-Situ** *Sensors*

These vertical cross sections of ozone and dewpoint clearly show dry, ozone-rich stratospheric air intruding into the upper troposphere over a horizontal ground track extending from north (left in the figure) to south (right). (The locations shown are CMI—Champaign, IL; BIB—Bible Grove, IL; CNG—Paduka, KY; and MEM—Memphis, TN.) The measurements were obtained from aircraft-mounted* in-situ *sensors as the aircraft was flown back and forth at different altitudes through the tropopause fold (from Warren Johnson and William Viezee; Atmospheric Environment, vol. 15, no. 7, pp 1309-1323, 1981).

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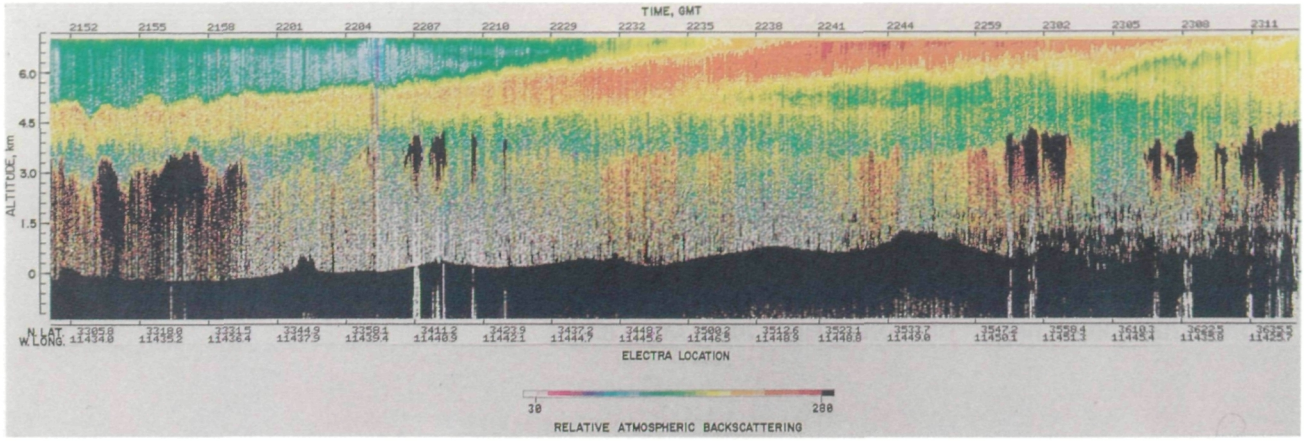

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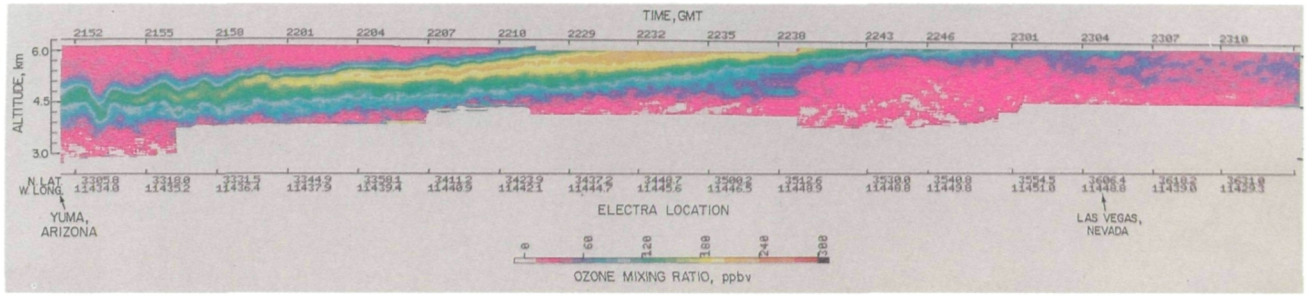

DIAL Ozone Measurement

Figure 4-5. Tropopause Fold Observations Using an Airborne Remote Sensor

These vertical cross sections of aerosol and ozone distributions were obtained through a stratospheric intrusion extending from north (right in the figure) to south (left) by means of a single pass of an aircraft equipped with a down-looking airborne lidar system. This DIAL (Differential Absorption Lidar) system measures relative aerosol distributions using a wavelength of 1064 nm, and ozone volume mixing ratio distributions at DIAL wavelengths of 287 and 300 nm (from E.V. Browell, et al., Tropopause Fold Structure Determined from Airborne Lidar and **In Situ** *Measurements, in Journal of Geophysical Research, vol. 92, no. D2, February 1987).*

4.3.6 Stratosphere-Troposphere Exchange: Airborne Observational Needs

Mid-Sized, Long-Range, High-Altitude Jet Aircraft (see 4.6 below).

Ultra-High-Altitude (>70,000 ft), Subsonic Aircraft (see 4.6 below).

STEP Payload Deployment. The 1984-87 Stratosphere-Troposphere Exchange Project (STEP) included the development and integration into an ER-2 of a large and varied array of meteorological, trace-gas, particulate, and radiation sensors, yielding the heaviest and most diverse payload of atmospheric instruments to fly in the stratosphere to that date. Hence, a significant advance in knowledge of stratosphere-troposphere exchange processes could be made by future deployments of the STEP package (probably with minor modifications) on an ER-2, rather than by major new multi-instrument or platform developments.

ER-2 Dropsondes. Development of an ER-2 dropsonde-deployment capability, to provide multiple profiles of temperature and humidity

below the ER-2 flight path (particularly through anvil and cumulonimbus clouds) would be very helpful, especially given the risks associated with ER-2 cloud penetrations. These multiple profiles would also be useful in documenting tropopause fold structures. Continued work is needed on the calibration and reliability of ER-2 wind-sensing instrumentation, including the high-resolution navigation system essential to deriving those winds.

Real-Time ER-2 Telemetry. Real-time telemetry of ER-2 data to its ground station would permit the experiment scientist (who must remain on the ground) to increase the scientific return of flights by altering the flight path in response to the meteorological, chemical, and radiative environment encountered and sensed by the aircraft. Although limited ER-2 telemetry capability now exists, it needs to be extended to the deployed sites from which the ER-2 operates. Also, links between the ER-2 atmospheric instruments, telemetry system, ground computers, and display devices need to be developed.

Coordinated Flights of Two ER-2's. Finally, coordinated use of two ER-2's would be very useful in exchange studies, as well as in studies of tropical cloud radiation, for example. One ER-2, flying at maximum altitude, could remotely map cloud and radiation structures with lidar and radiometers, while the second ER-2, equipped with *in-situ* or horizontally viewing sensors, could perform intensive sampling near cloud tops or the tropopause.

4.3.7 Clear-Air Mesoscale Circulations: The Scientific Challenge

Aircraft are currently used for *in-situ* observations of clear-air mesoscale circulations such as sea-breeze induced flow, mountain-valley circulations, down-slope wind storms, gust fronts and dry-lines, roll vortices, and circulations associated with baroclinic fronts. These circulations are generally too small (or occur on too-short temporal scales) to be resolved by conventional atmospheric (rawinsonde) observations, and are often very important in determining local-scale weather.

4.3.8 Clear-Air Mesoscale Circulations: Airborne Observational Needs

Flow Structure Documentation Capability. Since mesoscale circulations are often clear-air features, an airborne *Doppler lidar* would be particularly effective in documenting the flow structure. *Improved aircraft positioning* (such as the Global Positioning System) as well as a *safe dropwindsonde* would also be required to adequately document these features.

Raman Lidar. Profiles of water vapor are also needed to map the horizontal distribution within the circulations. A Raman lidar or related technology could be employed to provide high vertical resolution moisture structure.

Laser Doppler Velocimeter. Current fast-response air-motion sensing systems are mechanical in nature and typically rely upon either boom-mounted vanes or differential pressure ports installed on the nose of the aircraft, usually on the radome. Although these systems generally work reasonably well, they have several inherent problems, including flow-field distortion from the aircraft fuselage and boom vibration errors. A laser Doppler velocimeter, however, has none of these disadvantages because it is a remote sensor and does not require mechanical probes or booms exposed to air flow or vibration. It offers the possibility of all-weather performance because only a small window needs to be anti-iced, and a useful signal can be acquired

even in heavy clouds. In addition, the laser scattering approach avoids the empirical transducer calibrations necessary for systems based on vanes or pressure differences. Calibration of a laser Doppler velocimeter depends only on physical constants and geometry. In this sense, it provides an absolute measurement, with an accuracy as good as its precision. Laser air motion sensing has already been successfully demonstrated for the longitudinal air motion component. Future efforts should be directed to the development and evaluation of prototype scanning and intersecting beam systems that can measure all three components of the air motion.

4.4 *Radiative Processes*

The importance of clouds, especially stratus and cirrus clouds, in affecting the radiation budget of the Earth-atmosphere system, and thus the climate of Earth, is well known (see Figure 4-6). Differential heating of the Earth's surface in the vicinity of the edges of layered clouds can be a factor in the generation of mesoscale weather systems. There is a need to improve parameterization of the cloud-radiation processes in mesoscale and global models of the Earth's weather and climate. Radiation cloud studies are being conducted as important parts of the International Satellite Cloud Climatology Program (ISCCP) and the First ISCCP Regional Experiment (FIRE), discussed in Section 2.0.

4.4.1 Shortwave Radiation: The Scientific Challenge

The processes associated with the reflectance and absorption of incoming solar radiation need to be better understood in a variety of cloud systems. Key questions involve the role that mesoscale circulations play in determining horizontal extents of cloud layers and the influences of cloud-top-radiative-flux divergence on the development of cloud layers. More must be learned about the character of cirrus clouds and ice distributions in the tops of growing cumulus clouds in order to understand their radiative properties better.

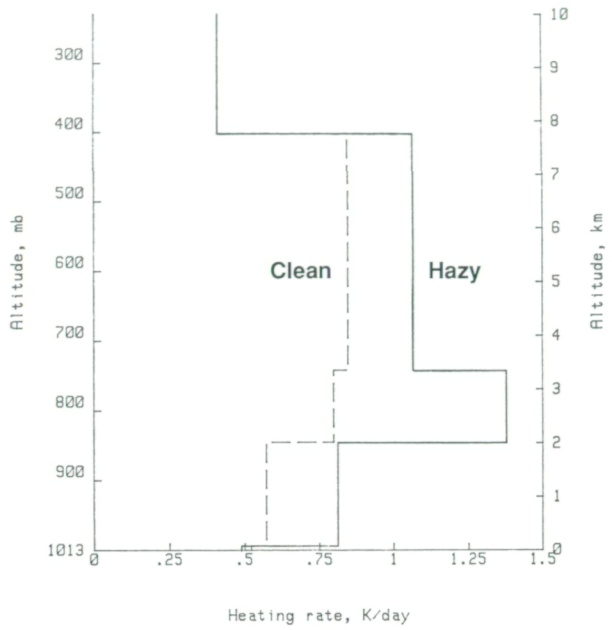

Figure 4-6.
NASA/NOAA Arctic Haze Measurements

Measurements with NASA radiometers aboard the NOAA WP-3D aircraft showed for the first time how the Arctic haze greatly increases the heating of the atmosphere during northern high-latitude spring. Other instruments on the WP-3D simultaneously documented the gas and aerosol composition of the haze.

4.4.2 Shortwave Radiation: Airborne Observational Needs

Cloud-Property Sensors and Ice Collectors. These systems are used in many atmospheric measurement programs, but improvements

are necessary to provide more accurate and reliable in- and extra-cloud particulate and moisture data to further our understanding of weather, climatological, and radiative processes. New or improved cloud-property sensors such as *lidar, multichannel radiometers,* and *ice collectors and detectors* are essential for many atmospheric programs. In particular, such improved sensors are needed for radiation programs (such as FIRE) that seek to understand the interactions of cloud microphysics and radiation.

Mid-Sized, High-Altitude Jet Aircraft. Since most of the shortwave radiation interactions occur near cloud tops, a suitable platform must be available to carry instrumentation to high altitudes (30,000 to 40,000 ft). The existing NOAA P-3s and NCAR Electra have ceiling limitations of 20,000 to 25,000 ft, which make them impractical for the *in-situ* study of cirrus clouds. In addition, studies of microphysical evolution near the tops of growing cumulus clouds require repeated penetrations of the cloud as it rises. Present NOAA and NCAR aircraft do not have this capability, as typical ascent rates of cloud tops exceed 10 m/s in expected supercooled or icing conditions. A mid-sized jet aircraft would be a good choice for a platform for these, and related, radiation/cloud measurements.

4.4.3 Longwave Radiation: The Scientific Challenge

Important questions to be answered by longwave radiative-process studies concern which radiative mechanisms control the net transfer of moisture between different layers in the atmosphere, and what role is played by mesoscale circulations in determining the horizontal extent of cloud layers emanating from convective updrafts. Answers to these questions require study of the absorption of longwave outgoing radiation by clouds and by clear air in order to improve parameterizations of radiative processes.

4.4.4 Longwave Radiation: Airborne Observational Needs

Characterization of Three-Dimensional Atmospheric Structure. Although the absorption of longwave radiation by clouds and cloud-free regions is fairly well understood, improvements in our ability to observe and document the three-dimensional atmospheric structure are required to understand the role of weather systems and associated mesoscale circulations, in altering the vertical distribution of longwave radiation absorption. Developments in *airborne Doppler lidars, scanning radiometers, and dropwindsondes* are needed.

4.5 Cloud and Precipitation Processes

Despite our broad knowledge of the general structure of storms, the need to understand the internal processes of storms requires research studies that continue to challenge our best scientific resources. *In-situ* observational data on internal cloud and precipitation processes for both the interpretation of surface-based radar data and for input to and verification of numerical models are inadequate or non-existent. The required observations can be obtained in sufficient spatial detail only from aircraft platforms, dropsondes, or balloons.

4.5.1 Cloud Microphysics and Dynamics: The Scientific Challenge

The interactions between the microphysics of clouds, precipitation development, and storm dynamics have been poorly studied because of the safety limitations regarding aircraft flight into the central storm regions. For example, we know too little regarding the ice phase in thunderstorms and its role in

precipitation formation and electrification, yet nearly all precipitation falling from convective clouds involves the ice phase. The primary areas of hail embryo generation and hail development are associated with thunderstorm cores of >35 dBZ,[1] and generally occur above the altitude attainable by the T-28 aircraft (the only suitably storm-hardened aircraft now available; see 4.5.2 below). Particle-sorting in the upper cloud levels and ice trajectories through storms are inadequately known, but are undoubtedly important to hail formation and growth. Little is known of the importance of shear zones to hail growth, charge-separation mechanisms, and storm dynamics. These and other processes have been modeled and are observable by radar, but a storm-penetration aircraft is our only means of obtaining *in-situ* observations of what is actually happening in the core regions of storms. These "ground-truth" *in-situ* observations are vital to our analysis of radar data, to our understanding of the complex mechanisms and interactions involved, and to the development of better simulation models.

Experiments flown by storm-penetration aircraft will yield important new research data on the electrical, thermodynamic, and dynamic mechanisms interacting within storms. Equipped with Global Positioning Systems (see Section 8) and other advanced navigation systems, near-field radiometric thermometers, and *in-situ* and remote probes, such aircraft can provide a direct look at non-hydrostatic pressure distributions in relation to water loading, buoyancy, and other parameters. An examination of cloud water contents (see Figure 4-7) and hail-growth processes in the upper portions of updrafts occurring in isolated multicelled thunderstorms requires penetration altitudes higher than the freezing level. In individual storms and in storm complexes, we need to make *in-situ* measurements of the interrelated mechanisms that lead to the formation of severe downdrafts and microbursts as well as storm outflow and entrainment. The examination of these processes requires aircraft penetration of high-reflectivity storm cores at all altitudes up to the top of the cloud system.

[1] A dBZ is a unit of radar reflectivity that is frequently related to storm intensity.

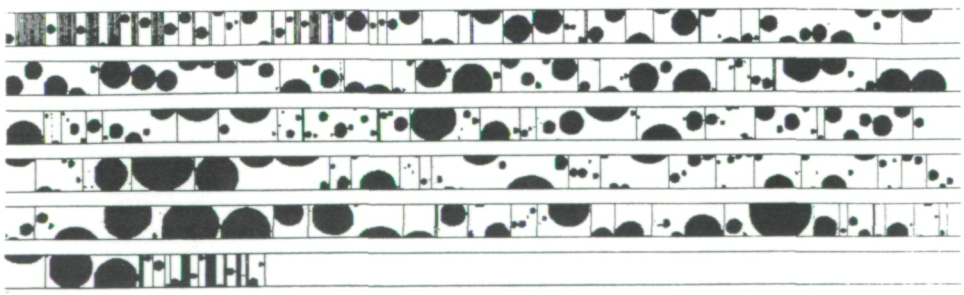

Figure 4-7. Raindrop Spectrometry in the Joint Hawaiian Warm Rain Project

As part of the 1985 Joint Hawaiian Warm Rain Project, data on raindrop sizes were collected through the use of aircraft instrumented with cloud and raindrop size-spectrometers. The figure shows a time-series measurement of raindrop sizes for a low-level penetration of a small precipitation shaft. The width of each strip is 3.2 mm. The surprising observation was that these drops were much larger in size than previously reported in measurements from orographic clouds. The presence of these large raindrops suggests that a number of widespread views on the formation and evolution of warm rain should be reconsidered.

4.5.2 Cloud Microphysics and Dynamics: Airborne Observational Needs

Many aircraft have been instrumented and used for cloud and meteorological research; however, only a few research aircraft have been capable of penetrating thunderstorm cores. Today only the T-28, operated by the South Dakota School of Mines and Technology (SDSMT) with base funding from the National Science Foundation (NSF), and the F-106, flown by NASA-Langley, have been hardened for storm penetration and are being used for storm-core research.

The SDSMT T-28 aircraft was armored and instrumented for hail research in the late 1960s. It has been in research use for nearly 20 years. Recognizing the age and flight limitations of the T-28, the NSF convened a Special Advisory Panel in 1985 to evaluate the adequacy of the T-28 to meet future research needs, and to make recommendations on the storm-core penetration aircraft and related instrumentation facilities and on how these facilities should be funded and managed.

Storm-Penetration Aircraft. One of the panel's recommendations was that an improved storm-penetration aircraft should be acquired and operated by an appropriate agency. This aircraft should have twin engines offering reliable operation in regions of heavy hail, icing, rain, and lightning. It should be "hardened" for penetration of large hail (2-inch diameter) and for minimum vulnerability to lightning, and should be stressed for high-g maneuvering loads. The aircraft should have a research-altitude capability to 45,000 feet and a flight endurance of 4 to 5 hours. These requirements point to a ruggedized, military-type aircraft.

4.5.3 Cloud Electrification: The Scientific Challenge

The mechanisms of hydrometeor charging and bulk charge separation remain poorly defined. It is believed that primary electrification occurs within the >35 dBZ cores of thunderstorms. It is known that electrification also occurs within developing storms and in cloud regions of <35 dBZ. Sailplanes and powered research aircraft have been used for observations of electric fields; hydrometeor parameters such as charge, phase, and size; and electrical polar conductivity in the <35 dBZ regions of storms. Such measurements have been highly useful in thunderstorm electrification studies. However, only a storm-penetration aircraft can safely obtain the critically needed measurements in thunderstorm cores.

4.5.4 Cloud Electrification: Airborne Observational Needs

Storm Penetration Aircraft and Electrical-Charge Measurement Devices. In addition to the storm-penetration aircraft described above, which could be used for direct *in-situ* measurements of cloud-scale parameters such as hydrometeor size and concentration, there is a need to develop or improve electrical-charge measurement devices, such as field mills, to measure the ambient electric charge in various regions within and outside a thunderstorm.

4.6 New Airborne Platforms Needed by Multiple Disciplines Within Atmospheric Science

In addition to the needs described above for the individual disciplines within atmospheric science, there are two important platform needs that apply to several disciplines.

Mid-Sized, Long-Range, High Altitude Aircraft. Current high-altitude (>35,000 feet) atmospheric research aircraft available to the scientific community either are quite small, with scientific payloads on the order of 1,000 to 3,000 pounds (e.g., NCAR Sabreliner, NASA

ER-2), or quite large, with payloads of 10,000 to 30,000 pounds (e.g., NASA DC-8). The smaller aircraft have limited space for instrumentation and research personnel, requiring customization of payloads. These restrictions often limit the aircraft to single-investigator use. Although the DC-8 is a very useful large aircraft, it is expensive to fly, and thus is normally reserved for research missions involving a number of investigators (typically 5 to15). In addition, DC-8 operations are normally limited to altitudes below 40,000 ft.

The above limitations in the current research aircraft fleet point to the strong need for a mid-sized jet aircraft with the following features and capabilities: a scientific payload with full fuel in excess of 5,000 lb, a range greater than 4,000 nm, an endurance greater than 9 hours, and a maximum altitude with full payload in excess of 50,000 feet. Such an aircraft would fit well within the existing gap between small and large aircraft, and would find extensive uses in various atmospheric science studies, including mesoscale and synoptic-scale meteorology (storm structure and dynamics); microscale meteorology, cloud physics, and convective storm structure (boundary-layer processes and dynamics); atmospheric chemistry (tropospheric and stratospheric chemistry and aerosols); and climatology factors (radiative effects of clouds and aerosols, ground-truth/air-truth for satellite sensors, and stratospheric-tropospheric exchange).

In the latter context, a mid-size jet could add greatly to capabilities for conducting research world-wide, and for determining climatological characteristics over large areas. It would provide the ability to cover most of the troposphere, and important portions of the lower stratosphere. Such an aircraft would be ideal as a platform for remote-sensing instruments and for dropping deployable sondes, which would even further extend the areal coverage of the measurements. It is likely that these far-reaching applications will assume even greater importance as more attention is directed to obtaining representative measurements of atmospheric variables for studies related to global climate.

Ultra-High-Altitude (>70,000 ft) Subsonic Aircraft. The ER-2 and its current instrument complement have yielded a wealth of information about mechanisms of stratosphere-troposphere exchange and about stratospheric chemistry, physics, and dynamics, especially in studies of the Antarctic ozone hole. But in most latitudes and seasons the bulk of interesting stratospheric chemistry occurs above the ER-2 ceiling (about 70,000 ft or 20 km). This region has traditionally been explored with balloons. Balloons have significant disadvantages, as described previously in Section 4.2.3. An aircraft to sample the 70,000- to 100,000-foot region would be of great value because this region contains many rapid vertical variations that are poorly understood. This poor understanding stems not only from a sparsity of measurements, but also from disagreements between measurements and models, and between different measurement techniques. The requirement for subsonic flight comes from the need to fly the subsonic air-sampling instruments now flown on the ER-2s and U-2s.

The disciplines that could be served by such an aircraft include stratospheric chemistry, dynamics, and physics. The aircraft could be used to carry instruments similar to those now carried by the ER-2s and U-2s to measure ozone, carbon monoxide, total reactive odd nitrogen, nitric oxide, nitrous oxide, water vapor, chlorine monoxide, bromine monoxide, whole air samples (post-flight analyzed for long-lived tracers such as methane, nitrous oxide, carbon dioxide, and Freons), aerosol size and composition, cloud particle size and shape, solar and terrestrial radiation, temperature, pressure, and 3-dimensional winds.

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Ocean Science: Scientific Challenges and Airborne Observational Needs

AIRCRAFT OBSERVATIONS provide unique information in the scientific study of oceanic processes. In particular, air-sea interaction processes and physical and biological oceanographic phenomena can be investigated with airborne remote sensors and aircraft-deployed *in-situ* sensors, in combination with traditional moored, shipboard, and spaceborne sensors. Oceanic processes that have mesoscale or larger lateral dimensions (>100 km) are particularly well suited for aircraft study. Synoptic, three-dimensional surveys of such processes can only be accomplished by aircraft, due to various limitations of ships (slow speed) and satellites (surface coverage only). Recent measurements of the structure of Gulf Stream meanders and eddies, which included the use of P-3-deployed temperature sensors, are exemplary of the combined ship/aircraft/ satellite/*in-situ* instrumentation approach, and show how this method of observing the ocean is, by far, more than the sum of its parts (see Figure 5-1).

5.1 The Scientific Challenge

Although the value of aircraft for *in-situ* and surface-process ocean studies has been demonstrated by the agencies involved in this type of research (primarily NASA, NOAA, and the U.S. Navy), aircraft usage in the overall oceanographic research community remains relatively low. In part, this is due to the traditional foci of the different research communities–NASA on airborne remote sensing, NOAA on airborne (and oceangoing) hurricane research, and the university community on shipboard, *in-situ* studies—but in recent years this tradition has exacerbated the lack of university scientist involvement in airborne research. This problem is manifested in the relative difficulty university scientists face in obtaining access to appropriate research aircraft compared to their access to ships. Until recently, the only long-range research aircraft that were reasonably available to the overall oceanographic community were the two NOAA P-3s, and they have schedule constraints due to their hurricane missions between June and October of each year. These aircraft also have range limitations that affect some types of oceanographic studies. A further impediment to the widespread use of aircraft in ocean science has been the very limited availability of appropriate air-deployable sensors. Since only a few variables can currently be measured with such devices, oceanographers continue to rely upon ships for their *in-situ* observational needs. This tends to keep the tradition of ship-going oceanography strong, which in turn does not encourage the development of new airborne and air-deployable oceanographic sensors. A "vicious circle" results: low aircraft usage gives the impression that aircraft techniques are not valuable, thus aircraft demands by

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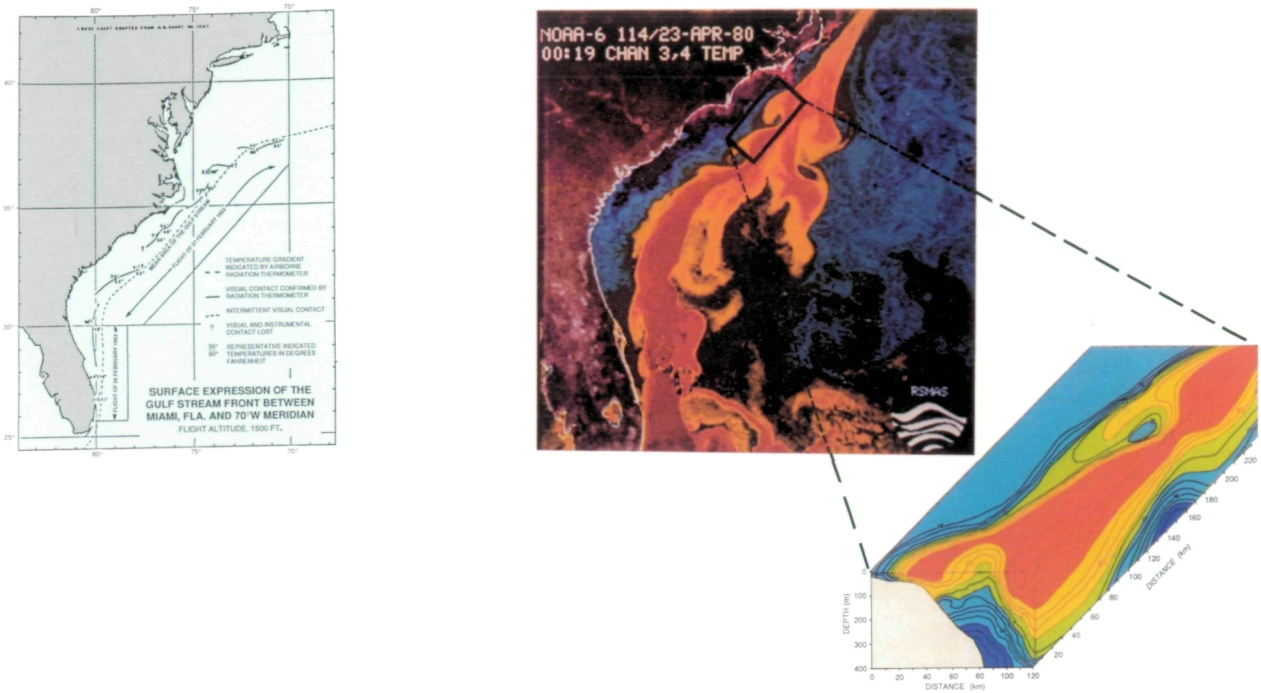

Figure 5-1. Research Aircraft Contributions to Gulf Stream Studies

The fine structure of the Gulf Stream front was first observed during an aircraft survey of the ocean surface-temperature field flown in the early 1950s (upper left). A downward-looking radiometer was used to locate the region of strong surface-temperature change associated with the shoreward edge of the Stream, which was found to have variations in location with spatial scales of tens to hundreds of kilometers. This Gulf Stream variability is now known to be due to frontal meanders and filaments, which are currently observed by satellites using advanced versions of the same type of radiometer used for the early aircraft measurements (center image; warmest surface temperatures are coded red). Although such satellite-observed surface temperature images are valuable, the complete, highly dynamic subsurface structure of Gulf Stream meanders and filaments may not be seen by satellites, nor synoptically mapped with traditional ship techniques. Recent aircraft surveys using air-deployed temperature profilers have given the only synoptic, three-dimensional views of these intriguing features (lower right), results that were obtainable only because of the speed and range of modern research aircraft.

oceanographers are low, which keeps the usage low...and so on.

Airborne remote-sensing instruments rarely evolve from the demonstration phase to operational tools for the oceanographer. One reason is that often the basic physics of the measurement is not understood by the user, and it is perceived that several engineers and technicians are required to operate the sensors and to reduce the data. One exception to this is the wide acceptance given within NOAA to the Stepped Frequency Microwave Radiometer (SFMR). This self-operating sensor measures sea-surface windspeed, even when there is precipitation between the aircraft and the ocean surface. An SFMR implementation at the National Hurricane Center is in the final stages of providing a real-time surface-wind measurement capability.

5.2 *Ocean Science: Airborne Observational Needs*

Improved Air-Deployable Expendable Bathythermograph (AXBT). The mainstay of aircraft oceanography continues to be the AXBT, which gives a temperature profile in the upper several hundred meters of the ocean. Even though it is widely used, the depth range, fall rate, and accuracy of the AXBT (all dictated by operational Navy specifications, not research considerations) are less than desirable for scientific studies. The performance capabilities of the AXBT must be upgraded. A depth range of 1,000 m (currently 305 m), temperature accuracy of 0.10 degrees C (currently 0.55 degrees C) and fall rate of 5.0 meters/sec (currently 1.5 meters/sec) are appropriate target figures. The relatively large production of the AXBT—approximately 20,000 units per year—is due to the U.S. Navy's needs. No other air-deployable expendable oceanographic instrument is available in this quantity.

Availability of a Suite of Expendable Profilers. There is a clear need for off-the-shelf instrumentation for the measurement of ocean currents, ocean salinity, and ocean optical properties. For the study of ocean currents, reasonable success has been achieved in the development of the AXCP and various near-surface current-following drifters; however, the availability of these is very limited and the costs are relatively high. An important tool for the study of ocean salinity—the Air-Deployable Expendable Conductivity-Temperature-Depth Profiler (AXCTD)—is still being developed. Assuming that its capabilities meet their targets (temperature and salinity determination accuracies of 0.03 degrees C and 0.05 parts per thousand, respectively; a fall rate of 3.4 meters/sec, and a depth range of 1,000 meters), this instrument could revolutionize hydrographic surveys of the upper ocean. The AXCTD is the most important aircraft oceanographic tool being developed, and its completion is crucial. The study of ocean optical properties would benefit if the newly designed light intensity/temperature profiler (XKT), which provides profiles of total downwelling light extinction coefficients and temperature, could be made air-deployable. Additional optical sensors—color and fluorescence profilers, for example—should be developed for ocean biology and flux studies.

Continued Development of Airborne Remote Sensors. Airborne remote sensors can be used to measure ocean surface temperature and salinity (see Figure 5-2), surface dynamic topography, ocean color and pigment concentrations, air-sea heat fluxes, and surface-wave fields. Active remote sensors currently in use include laser profilometers and lidars, used to measure wave activity bathymetry, chlorophyll-a, and other pigment concentrations in the ocean surface layer; microwave scatterometers and side-looking, imaging radars, which are used to determine surface roughness in the capillary-wave regime (an indicator of surface wind speed); and wide-band altimeters and wave spectrometers, which are high-temporal-resolution radars that are used to measure sea state, dynamic topography, wave elevation topography, and surface-wave spectra. One very promising new active remote-sensing technique is aircraft altimetric measurement of surface dynamic topography. This technique depends upon a precise knowledge of the aircraft's absolute altitude, which should be obtainable with a fully operational Global Positioning System (see Section 8).

Aircraft programs to study basic scattering mechanisms and to develop appropriate parameterization schemes are needed. For example, flight experiments are needed to determine the altimeter electromagnetic (em)

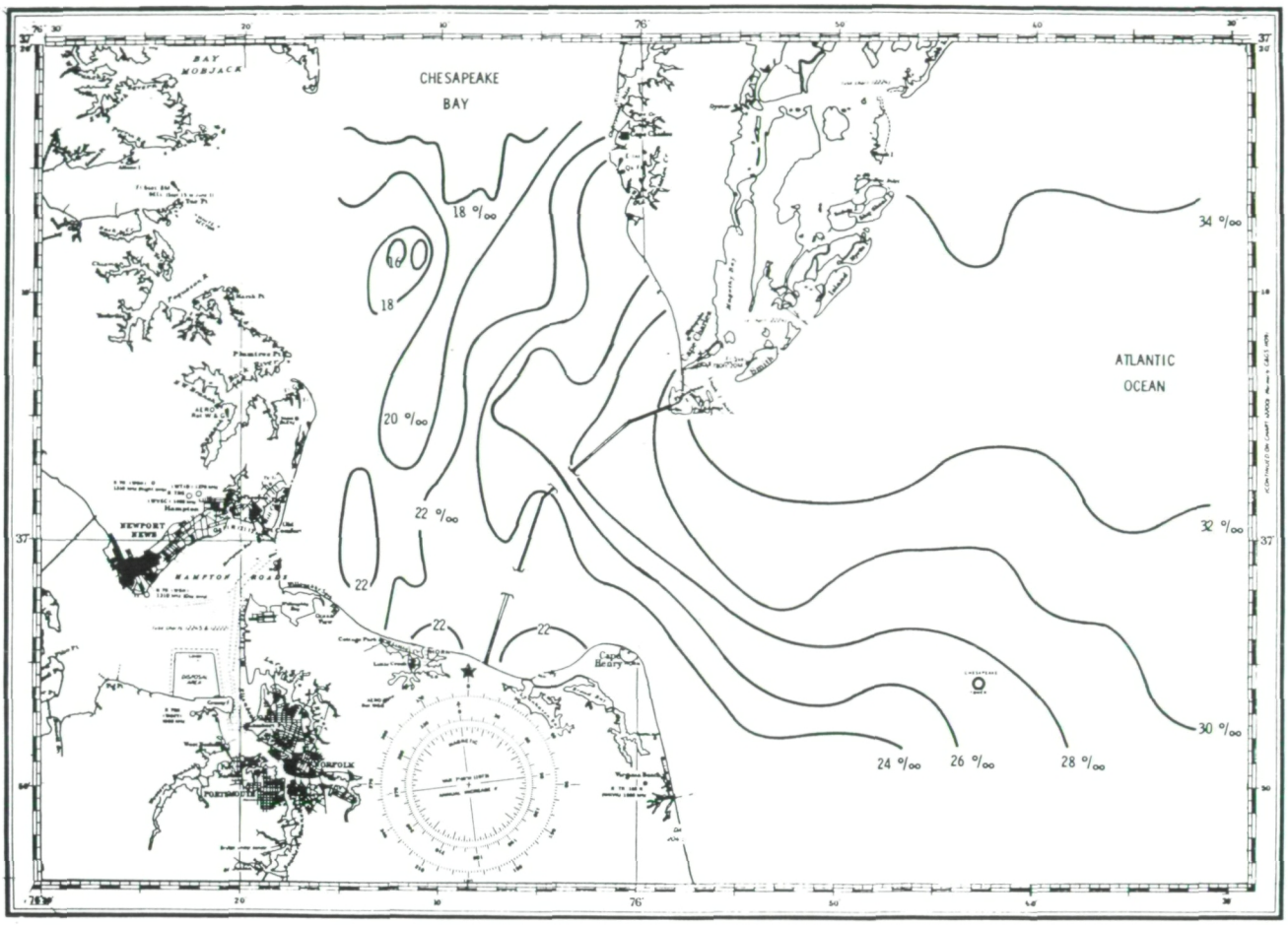

Figure 5-2. Chesapeake Bay Salinity Study — The Advantage of Airborne Mapping

The figure shows a plot of isohalines (lines of constant salinity) in the lower Chesapeake Bay on August 26, 1976. The increments are in two parts per thousand. The values were derived from airborne S-band and L-band microwave radiometers with nadir views. Mapping was accomplished by flying a total of 12 parallel east-west flight lines over a 25 x 50 mile area in 3-1/2 hours, and included 6,000 independent samples. By contrast, in 1972, in the aftermath of Hurricane Agnes, it took ships and helicopters 3 days to gather 180 point samples for the construction of similar maps. Hurricane Agnes grossly changed the salinity concentration of the Chesapeake Bay, threatening the health of shellfish.

bias at C- and Ku-band as a function of wind and wave conditions, because in-orbit determination of the bias is impractical, except on a statistical basis, and *in-situ* platforms (towers) are not nearly as well suited to the measurement task as are airborne platforms.

A vigorous airborne research program is also necessary in order to achieve a global air-sea flux measurement capability for weather and upper-ocean prediction and for understanding global climate change. The development of rapid-scanning, multipolarization scatterometers at Ku- and C-band frequencies should be encouraged.

Passive sensors in use include the infrared radiometer, the microwave radiometer,

and the ocean color imager, all of which measure electromagnetic radiation emanating from the ocean's surface and give information relating to surface temperature, salinity and color. Ocean surface temperature and color measured on swaths beneath an aircraft's flight track can delineate features in oceanic frontal zones and eddies. A knowledge of ocean color is a direct step towards an understanding of biological primary productivity. Simultaneous surface and subsurface temperature, salinity, and color measurements can reveal the relationship between this productivity and the physical domains within which it occurs. Airborne ocean-color remote sensors will be the only way to determine ocean color over large areas during the next few years of global ocean science studies, since no satellite color sensor will be in orbit during that time.

Long-Range, Large-Payload Aircraft. Oceanographic research requires aircraft that can transport sensors to the appropriate ocean location and then provide enough operational time on station to deploy a grid of *in-situ* sensors, and/or fly remote sensors in a pattern that will cover the feature of interest (e.g., a Gulf Stream ring or an equatorial jet). Such surveys will often be done at low altitudes, thereby consuming fuel at a greater rate than during high-altitude cruise. A very-long-range (4,000-6,000 nm), large-payload aircraft is therefore the most needed platform for oceanographic studies. This platform would serve two purposes that are beyond the capability of existing research aircraft. First, it would allow access to various oceanic locations that are presently inaccessible by reason of distance — certain areas in the central Pacific, for example. Second, it would provide suitable on-station time for complex survey patterns with appropriate consideration given to low on-station altitudes. A C-130 with added fuel capacity is a good candidate aircraft for this type of mission. This aircraft would also allow the deployment of large objects, such as drifters or subsurface moorings.

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Terrestrial Science: Scientific Challenges and Airborne Observational Needs

ACCESS TO OBSERVATIONAL data from aircraft platforms is a critical element of research in the terrestrial sciences (geology, biology, hydrology, and human cultural practices). Aircraft research programs not only provide continuing refinement of an understanding of the constituent elements of Earth processes, but also allow testing and refinement of the Earth-observing sensors necessary to gather the data. Further, the evolution of spaceborne sensors typically requires an extended period of *in-situ* measurements onboard research aircraft. Aircraft programs are thus critical to the realization of major agency goals in the terrestrial sciences.

6.1 Biology and Ecosystem Science: The Scientific Challenge

Sensors flown on aircraft have provided essential radiometric data for studies of the biosphere throughout the history of remote sensing. The characteristics of these airborne sensors vary widely with regard to spatial, temporal, and spectral resolution; radiometric quantization; angular observing capability; wave polarization; and phase shifting. These sensor characteristics can be used in various ways to provide information on vegetation properties.

The most urgent scientific need in the biospheric sciences is for a broad data base on state variables of vegetation communities and their associated environment. A data archive of these variables is required for input into global and regional models describing ecosystem processes. These potentially measurable state variables include biophysical parameters such as leaf-area index, visible light absorption, and total biomass; biochemical variables such as canopy nitrogen and lignin content (see Figure 6-1); thermal and environmental properties such as canopy temperatures, combustion radiant temperature, and soil moisture; and topographic conditions such as elevation contours.

Different vegetation parameters exert their influence on radiometric interaction at often different scales. For example, the annual dynamics of leaf display can be reasonably well represented at global scales using the low spatial and spectral resolution but high temporal resolution (24 hour) of current satellites. High spectral resolution is required to understand the unique contribution of biochemical absorption to canopy reflectance. High time resolution (hours) and low-gain thermal sensors throughout the infrared are necessary to achieve an understanding of the rapidly changing conditions in wildland fires.

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A Research Challenge: The Biosphere

The quantitative estimation of canopy biochemical content is a vital parameter in the study of biogeochemical cycling. The radiometric expression occurs as heavily overlapped absorption features of the organic compounds that make up all foliar mass. The research challenge is to extract the concentration or content of such compounds in plant canopies by understanding how these properties combine to affect overall canopy reflectance patterns. This problem is related in a general way to the problem of discriminating mineral substrates but is different in the common occurrence of all organic compounds in every plant reflectance signature. A similar situation prevails in the thermal characterization of the combustion zone of wildland fires related to the production of volatiles and particulates. Sensor designs to measure both ambient and very high temperatures are needed for aircraft deployment.

In addition to taking advantage of the multitude of sensor performance characteristics applicable to biology, remote sensing by aircraft can also perform a special role in the investigation of dynamic phenomena. Aircraft, unlike most spacecraft, can remain on-site for repeat measurements across time scales of hours to weeks, often without sacrificing desirable sensor performance characteristics. Advances in the development of methods to rapidly deliver data to the scientific community may prove to be valuable to the study of disease vectors that require unusually time-critical decisions. Satellite data-delivery performance is inadequate for this task. However, despite the potential scientific advantages of aircraft data-return capabilities, the advantage is rarely realized at present because of the difficult logistic, financial, and usage demands on currently available aircraft. A potential long-term solution to this problem involving aircraft simulation capability in the Earth Observing System (Eos) era is discussed later in this section.

6.2 Biology and Ecosystem Science: Airborne Observational Needs

Despite a relatively robust history of the application of aircraft and satellite sensor data to biospheric science, the biospheric science community has often had to use sensors not specifically designed for their needs. Even so, the research community has made effective use of nearly all available sensors. Concepts for sensor performance criteria more suitable for the acquisition of critical biological measurements are now beginning to emerge and will enable this community to better formulate and articulate their requirements.

Eos Emulation. Many of the most pressing scientific questions involving the biosphere, such as the interaction of the biosphere with aquatic bodies and the atmosphere, demand multidisciplinary research approaches. Generally, these questions cannot be addressed adequately with only one or two sensor packages but require information derived from many sensor sources. As part of the upcoming

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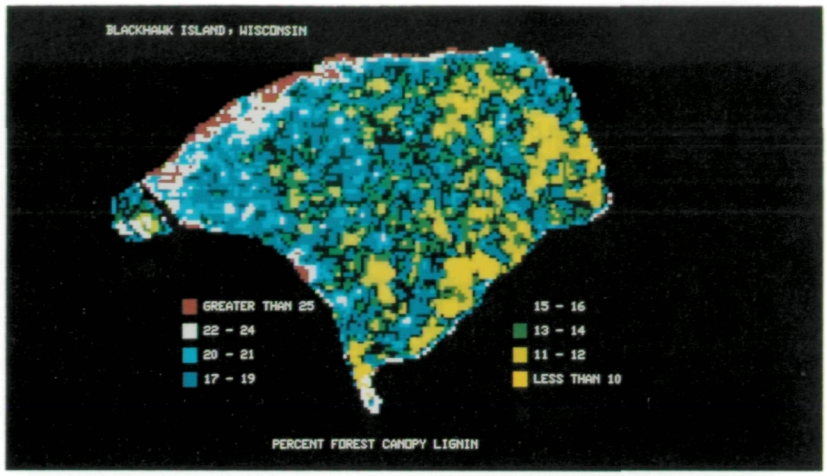

Figure 6-1.A. Forest Canopy Lignin Concentration

Spatial distribution of estimated lignin concentration of forest canopies on Blackhawk Island, Wisconsin.

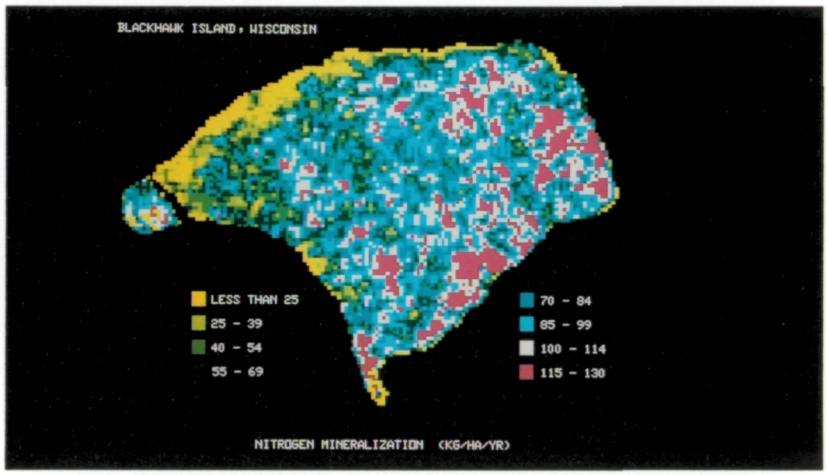

Figure 6-1.B. Nitrogen Mineralization of Soils

Spatial distribution of predicted annual nitrogen mineralization of soils on Blackhawk Island, Wisconsin.

The biochemical makeup of leaves in forest canopies is related to how leaves decompose and release their nutrients, such as nitrogen. These biochemicals also influence how canopies reflect solar radiation. NASA aircraft, such as the C-130, now carry high spectral resolution sensors, such as JPL's Airborne Imaging Spectrometer, to acquire spectrometric images of forest canopies. These data were analyzed by derivative spectroscopic techniques by scientists at ARC (D. Peterson) and the University of Wisconsin (J. D. Aber and C. A. Wessman) to estimate biochemical makeup. The structural chemical, lignin, which makes leaves slowly decompose, has been estimated and its distribution has been mapped across Blackhawk Island, an area of mixed northern hardwoods and conifers in Wisconsin. Since high lignin content (oaks and conifers) means slow decomposition rate and less conversion of organic nitrogen to mineral forms, while low lignin (maples) means rapid processes, lignin distribution can be used to predict patterns of annual nitrogen mineralization in the soils, the first time this has been possible.

international Space Station program, NASA will launch a series of large Earth-observing polar platforms called the Eos. Eos will include a variety of multidisciplinary sensor packages that will be of great value to all of the terrestrial sciences. The development of an aircraft simulation capability to emulate the simultaneous measurement capability of Eos would be beneficial in providing the biological community a chance to break new research ground in mesoscale studies and to prepare for the Eos era.

6.3 *Hydrology: The Scientific Challenge*

The long-range goals of hydrologic research are to utilize remote-sensing technology to improve our knowledge in several areas, including storages and fluxes in the hydrologic cycle, the relationships between hydrology and climate, the role of hydrology in the Earth's biogeochemistry, and the role of snow and ice in the Earth's hydrology and climate. In hydrologic studies, airborne remote-sensing instruments are primarily used to provide capabilities not yet found on satellites, or to provide more intensive temporal or spatial sampling than is possible from space. In addition, measurements of surface fluxes and trace gases from aircraft are used in hydrologic and climatic research. *In-situ* surface measurements can only estimate these fluxes over spatial scales of a few tens of meters, while aircraft can extend the range of measurements to encompass hundreds of kilometers.

In the active microwave (radar) regime, most of the data used for scientific research in hydrology have come from aircraft instruments; accommodation of these instruments on spacecraft is not yet mature. In the passive microwave regime, the available and planned satellite instruments have relatively coarse spatial resolution; therefore, aircraft sensors must be utilized for studies where spatially intensive sampling is necessary. As an example, near-surface hydrologic responses to thunderstorms can be observed using a combination of ground- and aircraft-based instruments, with airborne radars and radiometers remaining on-station as water infiltrates and evaporates following storm passage. Spaceborne instruments cannot observe continuously throughout the duration of these processes.

In the thermal and reflected solar wavelengths, spaceborne instruments (e.g., the Landsat Thematic Mapper) are well developed. However, satellite data with high spectral resolution in these wavelengths will not be available until the Eos era. Currently two aircraft instruments provide these data, providing not only an observational test capability but also an environment for the biological and ecological science communities to develop skills and algorithms in preparation for the Eos era. Although the Thermal Infrared Multispectral Scanner (TIMS) is used primarily in the geological sciences, the spectral bands allow for atmospheric correction to surface temperature measurements, and these are of crucial importance to regional estimates of evapotranspiration. In the visible and near-infrared wavelengths, the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) provides data in 224 spectral bands from 0.4 to 2.5 um. For hydrologic research, these data are necessary for examination of nutrient loading in streams and lakes, for estimation of the spectral albedo of snow and ice, and for spectral examination of vegetation. (Vegetation has a significant impact on several hydrologic processes: runoff, infiltration, and evapo-transpiration.) Scientists are only beginning to explore quantitative relationships between such parameters as precipitation history, soil moisture, leaf area, humidity, and insolation. Remote sensing is a necessary bridge between

in-situ field observations and regional or continental-scale documentation and understanding of changes in both climatic and hydrologic conditions. Because sensor requirements are poorly developed for studies of vegetation and hydrometeorology, aircraft are the natural test beds for instrument definition and development prior to spacecraft deployment.

6.4 Hydrology: Airborne Observational Needs

Humidity Sensors. The measurement of water vapor in the atmosphere is of central importance, yet remains a problem area in hydrological studies. Current techniques are limited by instrument drift, slow time response, and insufficient sensitivity to detect the smaller amounts of vapor in the upper troposphere and the stratosphere. Development of radiometric-absorption, cryogenic-mirror, and other promising instruments should be vigorously pursued. Current limitations in this area are holding back progress in water-vapor transport studies, atmospheric chemistry, satellite image analysis, and cloud physics.

Multiple-Payload Platforms. The difficulty currently facing some multidisciplinary experiments that use remote-sensing data from several sensors is that space for sensors on an aircraft is restrictive. Synergistic use of multiple instruments is therefore difficult unless the experiment is large enough to justify several aircraft. In future acquisitions of remote-sensing aircraft, vehicles are needed that can carry and operate several sensors, collecting data throughout the electromagnetic spectrum.

6.5 Human Cultural Phenomena: The Scientific Challenge

Aircraft observations have been used extensively over the years to gain an improved understanding of human cultural practices. The cultural phenomena observable from aircraft primarily consist of human spatial distribution over the global surface, and how humans interact with their environment. This interaction varies by location and through time depending on a complex set of biophysical, geochemical, socioeconomic, political, and religious factors. From the use of aircraft data for timber harvest inventories, to the mapping of urban/suburban sprawl, the monitoring of toxic-waste facilities, and the modeling of agricultural production, these data have provided useful information concerning the past, present, and potential future status of our environment. These human cultural information needs have spawned sizable national interagency aerial photography programs, and the resulting photographic data base is an extremely valuable asset to the scientists working in this arena.

As concerns related to the effects of our increasingly industrial/technological cultures on our global environment have increased, the use of aircraft systems for addressing these problems has also expanded. From examinations of agricultural production, urban planning, and resource exploration, to studies involving the identification of earthquake hazards in urban areas and the reverse-trajectory modeling of the movement of contaminated ground water to potential source areas, aerial imagery has played an important role in field and laboratory investigations. Yet, perhaps the best use of imagery acquired from aircraft for the study of cultural phenomena is achieved when these data are employed in a multistage sampling strategy along with ground- and satellite-acquired data. Employing this multistage sampling methodology permits both the quantitative and qualitative extrapolation of local data to progressively larger and larger areas. Limits of such extrapolation must be developed for a variety of

specific studies. In addition, the use of remotely sensed data for modeling both the spatial and temporal aspects of cultural processes can and will benefit from studies employing aircraft data.

6.6 Human Cultural Phenomena: Airborne Observational Needs

Rapid Turnaround of Aircraft Sensor Data. A major concern in the study of cultural processes is the ability to provide information to a potential user rapidly enough to meet their needs. Information concerning the health and vigor of agricultural crops and levels of toxic pollution are but two examples of important applications in this respect. Efforts should be made to provide for the rapid turnaround of aircraft measurement data for the study of a variety of cultural phenomena. Progress in this area would significantly enhance our understanding of the need for, and pitfalls associated with, the provision of this type of data delivery from advanced spaceborne sensor systems.

6.7 Geology (Lithospheric Science): The Scientific Challenge

The goal of lithospheric science is to improve our fundamental understanding of the origin and evolution of the continental crust and the nature of the surface and subsurface processes that have modified the crust through time. Advances in lithospheric science directly contribute to advances in our understanding of the long-term changes in Earth's environment that have influenced the development of life on the planet and, ultimately, the use of the planet by humankind.

The conceptual framework of lithospheric science now accepts plate tectonics as a process that has operated to assemble and modify the continents through time. The provision of observational evidence for plate tectonics is an early and revolutionary contribution of airborne science.

The complex history of plate tectonics, and the history of changing climate that accompanied it, is recorded in continental rocks.

Plate Tectonics

Early in the history of the Earth, Pangea, a supercontinent composed of most of the continents, is postulated to have existed. Although the causes for fragmentation of Pangea are not well understood, scientists have suggested recently that impacts of asteroids may have played a role in triggering plate tectonic activity and associated volcanism. Changes in the distribution of the continental crust probably affected Earth's rotation and polar motion. Fragmentation of Pangea caused major changes in ocean and atmospheric circulation. Episodic volcanism, associated with periods of major deformation, influenced evolution of the atmosphere. Worldwide climatic events over the last few tens of millions of years caused major changes in landscape-forming processes. Recent scientific theories have suggested that impacts from extraterrestrial materials may have played an important role in causing these climatic changes, in influencing episodic volcanism, and in altering the Earth's magnetic field. The ongoing studies of these and other issues related to plate tectonics have relied on airborne magnetic surveying techniques. (See Figure 6-2.)

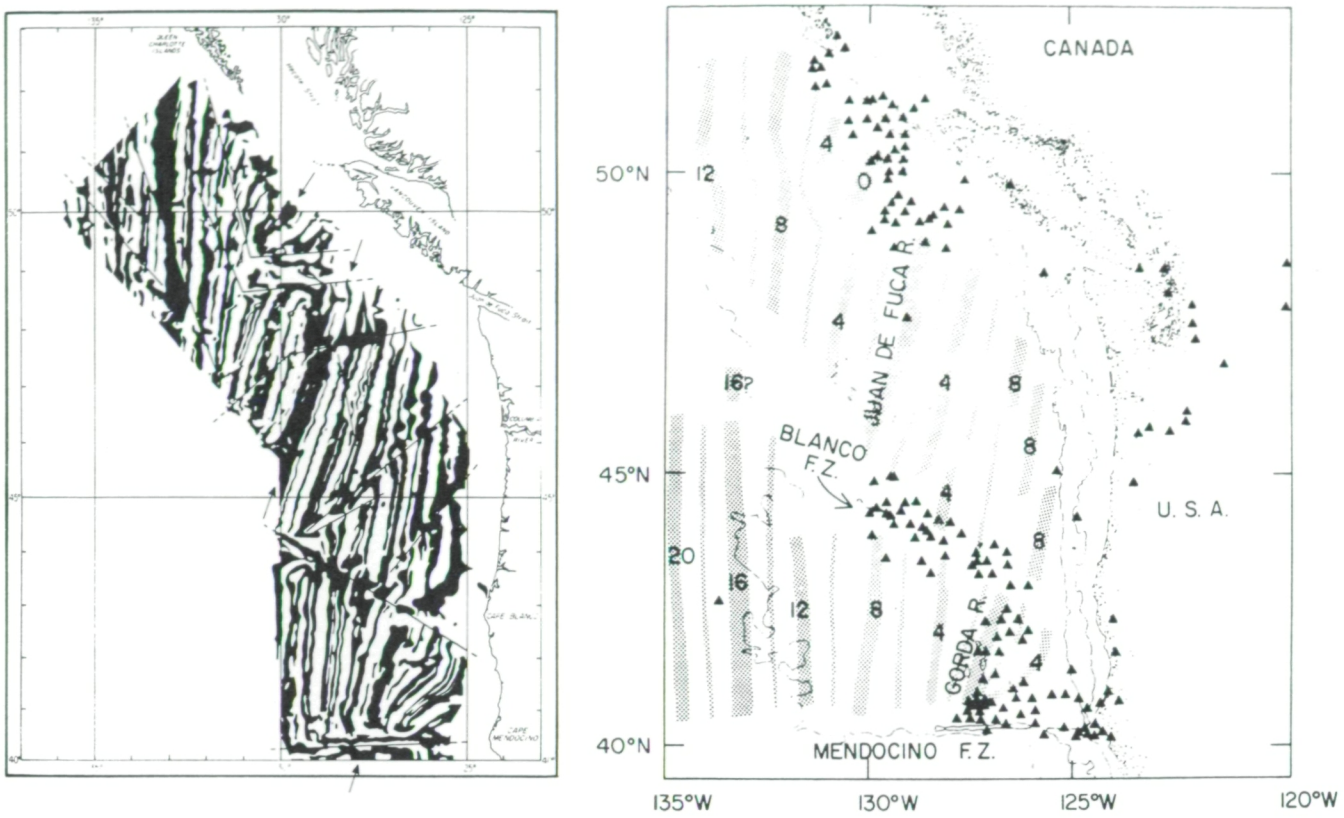

Figure 6-2.A. Magnetic Anomalies in the Sea Floor

Sea-floor spreading magnetic anomalies southwest of Vancouver Island. Positive anomalies are shown in black. Straight lines indicate faults offsetting the anomaly pattern: arrows indicate segments of ridges (from Vine, Science, v. 154, pp. 1404-1415, 1966).

Figure 6-2.B. Earthquake Epicenters on the Sea Floor

Earthquake epicenters (triangles) and sea-floor age (in millions of years before present) near the Juan de Fuca and Gloria ridges (from Atwater, GSA Bulletin, v. 81, pp. 3513-3536, 1970).

The most spectacular scientific discovery attributable to magnetic surveying is that of sea-floor magnetic stripes (Figure 6-2.A). These stripes provided the critical evidence in support of the theory of sea-floor spreading, the basis of plate tectonics. The magnetic stripes indicate that new sea floor, as it forms at the mid-ocean ridges, becomes magnetized in the prevailing direction of the Earth's magnetic field. As the sea floor cools it is displaced by younger sea floor and moves away from the ridge. The stripes alternate in polarity due to reversals of the Earth's magnetic field. Because the geomagnetic reversal time scale is known from paleomagnetic studies on land, the pattern of magnetic stripes allows the age of the sea floor to be determined (Figure 6-2.B). Today, the majority of the world's ocean basins have been dated using these magnetic stripes.

There are numerous opportunities for airborne geophysical and remote-sensing contributions to the unraveling of this record.

The complex, heterogenous nature of the continental lithosphere brings with it a need for multiple ways to observe the Earth. For example, regional tectonic history can be reflected in surface composition, morphology, gravity, and magnetic fields. These characteristics can be observed using radar, spectral reflectivity in visible and infrared bands, thermal and microwave emission, gamma-ray spectral emission, gravimetry, and magnetometry—all of which can be done from aircraft. Independent lines of evidence that lead to a consistent conclusion are a central measure of the validity of that conclusion in solid-Earth science. Solid-Earth scientists need access to all these methods of observation; in many cases, the value of the data are enhanced substantially by their synergism, and simultaneous measurement from a single platform is the preferred approach to providing this capability.

Aircraft observations are fundamental to the understanding of the interrelations of landscape attributes in different physiographic settings. Aircraft observations are the most efficient means by which laboratory- and ground-based observations can be extended to observations from space. Aircraft instruments now have bandwidths approaching those of laboratory instruments, and new, important spectra are being discovered that have great importance for geoscience investigations (e.g., Buddingtonite, an ammonium feldspar associated with low-temperature hydrothermal systems). However, the utility of several portions of the electromagnetic spectrum has yet to be investigated, and some geophysical aircraft techniques have great promise for advancement in this area.

In the late 1990s, NASA will fly the first Eos platforms in conjunction with the manned space station. An aggressive program of aircraft observations is needed to prepare the science community to use the instruments that will be flown on Eos. Among the instruments that need to be supported are a high-resolution imaging spectrometer (HIRIS) and an Earth-observation synthetic aperture radar (EOSAR). HIRIS will have 196 spectral channels with 9-nanometer bandwidths, 30- meter spatial resolution, and 30-kilometer swath width. EOSAR will be a three-frequency, quadpolarization radar with multiple-depression-angle capability and 25-meter spatial resolution. If the terrestrial science community is to make efficient and valuable use of these advanced spaceborne instruments, data sets and instrument characteristics should be established through airborne experiments as soon as possible.

6.8 Geology: Airborne Observational Needs

High-Altitude Platform. The greatest current limitation to the advancement of terrestrial science is the availability of aircraft platforms for scientific investigations. Airborne observations through the major portion of the Earth's atmosphere are required if aircraft observations are to be readily extended to orbital altitudes. Therefore, the availability to lithospheric scientists of high-altitude aircraft platforms such as NASA's ER-2, is critical to the success of their program.

AVIRIS and an Advanced TIMS. NASA's second ER-2 aircraft should be dedicated to the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS). Additionally, an advanced Thermal Infrared Multispectral Scanner (TIMS) should be developed for flight at altitudes above 4 km. This advanced TIMS

instrument should include channels in the 3- to 5-um and 8- to 14-um portions of the spectrum. It could be flown on the NASA DC-8 along with other visible and reflected-infrared imaging instruments.

NASA SAR and DC-8 Availability. NASA's DC-8 aircraft has been modified to carry a multifrequency/multipolarization SAR system. The current configuration of the SAR system allows simultaneous collection of L-, C-, and P-band data with quad polarization. Although the SAR could be of significant value to the lithospheric sciences, particularly if it is possible to collect P-band data at a 70-degree depression angle, availability of the DC-8 platform to the lithospheric science community has been a continuing problem.

Access to Modernized (Post-GPS) Mapping Data. Airborne geophysical measurements offer the most cost-effective means of obtaining information about the gross structure and composition of the Earth's crust. The advent of navigation by the Global Positioning System has reduced positional errors—usually the dominant source of errors on aeromagnetic maps—by factors as great as 10. Thus, new navigational technology has rendered most existing aeromagnetic maps obsolete. Furthermore, developments in data-processing and display technology have enhanced the utility of geophysical data sets, especially for investigation of regional to continental-scale areas. The geoscience community needs regular access to modernized maps and mapping capabilities.

Gravity Measurement Techniques. Precise navigation has also brought the possibility of measuring gravity from airplanes, which could rapidly provide information about density variations in the crust. Several technical approaches are being explored. These evaluations need to be completed so that more deployable systems can be made available to the research community.

A Comprehensive Airborne Geophysics Program. Airborne geophysics holds the greatest promise for major breakthroughs in lithospheric science. Aeromagnetic, electromagnetic, airborne gamma spectrometry, and airborne gravity measurements are currently being utilized by many countries for general lithospheric investigations. Australia and Canada have effectively utilized these techniques for investigations of large and poorly mapped areas. Although the United States has pioneered the development of spaceborne gravity and magnetic techniques, it has not effectively supported a comprehensive airborne geophysics program. Such a program should be supported, possibly as an interagency venture.

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Cryospheric Science: Scientific Challenges and Airborne Observational Needs

THE EARTH'S CRYOSPHERE consists of four main elements: sea ice, seasonal snow on land, land ice (including glaciers, ice sheets, and ice shelves), and permafrost. The time scales on which these elements impact human activity range from daily to seasonal for sea ice and snow, and to annual and decadal for ice sheets and glaciers. Our knowledge of the cryosphere, especially its seasonal and interannual variability, has increased dramatically since the advent of airborne and satellite remote sensing. As in other disciplines, aircraft have played a valuable role in the development of instruments and techniques for remote sensing of the cryosphere.

Airborne remote sensors have both complemented and paved the way for satellite observations, monitoring and measuring key cryospheric variables including the extent, concentration and age of sea ice; the extent, depth and water equivalent of snow cover; and the elevation, thickness, accumulation rates, ablation rates, strain rates, horizontal velocities, and iceberg calving of ice sheets and glaciers. The scientific uses of these data include the calculation of polar heat and mass budgets; oceanic water-mass modification resulting from vertical heat exchange, mass and momentum fluxes at the sea surface; and the horizontal (largely meridional) fluxes of heat and fresh water in the form of ice.

Glaciers, both those in polar regions and those at high altitudes in the tropical and temperate zones, contain the most complete record available of atmospheric chemistry, particulate concentration, and temperature for the last 100,000 years. Ice cores have optimum scientific value when their ice-dynamics content is understood; airborne radar measurements of ice-surface and bedrock topography provide this glaciological information.

Much remains to be done in terms of fully utilizing existing cryospheric data sets, developing new remote-sensing techniques for monitoring the cryosphere, and understanding the role of the cryosphere in the global climate system. Airborne science programs have played a unique role in the development of cryospheric observational techniques, and are expected to play an even larger role in the development of multisensor systems for observing and understanding the cryosphere as a key element in the atmosphere-hydrosphere-cryosphere system.

7.1 Sea Ice Studies: The Scientific Challenge

Satellite data from visible, infrared, and microwave sensors provide information on the global distribution and variability of sea ice. In contrast to visible and infrared measurements, passive microwave imagery allows

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coverage regardless of cloud cover or light level. Furthermore, although passive microwave observations are at a much coarser resolution than the visible or infrared observations, they do provide complete polar coverage with as little as 1 day of data. For these reasons, passive microwave radiometry has emerged as a tool of primary importance for monitoring polar regions. The development of active techniques, such as the synthetic aperture radar (SAR), is a few years behind the development of passive microwave techniques, but programs are underway to provide data for both operational needs and scientific research.

The development of satellite microwave remote-sensing techniques for sea ice research has been and will continue to be closely coupled with aircraft programs, not only because of the singularly inaccessible nature of the polar environment, but also because of the requirements of spatial resolution and areal coverage. Launched in 1972, the Nimbus-5 Electronically Scanning Microwave Radiometer (ESMR) led to the first accurate determination of polar sea ice extent and concentration. This effort was preceded in 1970 by NASA aircraft flights, which demonstrated the utility of using microwave radiances for distinguishing between ice-covered and ice-free ocean areas.

Since 1970, advances in sea ice radiometry have resulted from polar aircraft missions coordinated with major international polar experiments. Approximately 80 percent of the aircraft flights made during these experiments over the past 15 years were made by the NASA CV-990 Galileo I and Galileo II Airborne Laboratories. These aircraft provided the requisite range and altitude capabilities for carrying out successful microwave field experiments, and ultimately led to the development of multichannel passive microwave sea ice algorithms currently used for sea ice and climate research, as well as for operational needs.

More recently, a concerted effort has been initiated to make full use of SAR observations over sea ice, in preparation for routine application to research problems of SAR data to be acquired from the ESA Remote Sensing Satellite (ERS-1), the Japanese Earth Resources Satellite (JERS-1), the Canadian Radarsat, and the Earth Observing System (Eos) platform. Flights in March 1988 of the JPL SAR aboard NASA's DC-8 over the Beaufort and Bering seas provided complete polarimetric data sets at three frequencies (P-, L-, and C-band) over a range of ice types (see Figure 7-1). Multichannel passive-microwave data were acquired at the same time and ongoing analysis indicates that these data will significantly enhance our ability to interpret satellite data from both the SAR and passive-microwave radiometers. Additional data will be required from future aircraft sorties during different seasons, over both the Arctic and the Antarctic.

In sea ice studies, the overall scientific need is to understand the role of sea ice in the global climate system. To accomplish this, we must address several important questions such as what the spatial and temporal variations of sea ice are; how the oceanic, atmospheric, and radiative processes drive the interannual and seasonal variations of the sea ice cover; what role arctic and Antarctic polynyas play in water mass modification; and what the relationship is between sea ice and oceanic productivity. To address these concerns, we need to maintain, validate, and extend global satellite data sets of key sea ice parameters. These parameters include sea ice extent, sea ice concentration, and sea ice age. Aircraft experiments have played, and will continue to play, a key role in satisfying these requirements.

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The utility of historical and newly acquired sea ice data sets for use in climatological studies depends critically on our ability to define the accuracies of these data. Algorithms that generate the sea ice parameters from raw observations are themselves subjects of scientific research; the scientific uses of the geophysical data sets call for stringent accuracies.

The verification of the accuracies of the derived sea ice parameters is a critical component in the development of these global data sets. To achieve this verification, validation programs that include aircraft flights are vital. Aircraft observations serve two purposes. First, surveillance by aircraft allows high-resolution microwave measurements of sea ice concentration and ice type to be compared with corresponding measurements made from a satellite over several "footprints," thus providing a direct check on the spacecraft algorithm over selected regions of the Arctic and Antarctic. Second, the capability of the aircraft to conduct a focused study of subfootprint conditions is needed to understand, for example, microwave variability due to variations in snow depth, ice type, and surface roughness.

7.2 *Sea Ice Studies: Airborne Observational Needs*

Simulation of Spaceborne Multiple-Sensor Sets. There is a critical need for an airborne capability to simulate spaceborne sensors planned for the 1990s for the purpose of developing techniques to utilize combinations of such sensors. In contrast to spaceborne sensors, sensors on aircraft can provide the requisite beam-filling capability needed to develop new techniques for exploiting the potential of new data sets and to validate existing methods used with current data sets. For example, there is a need to develop and deploy airborne multifrequency/multipolarization SARs to

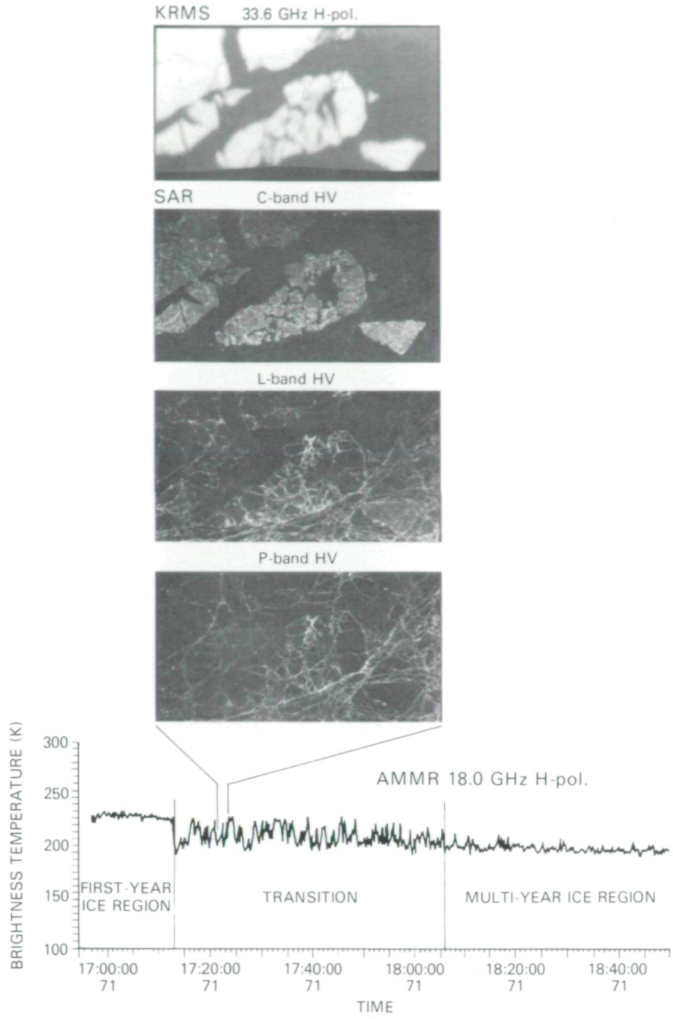

Figure 7-1. Sea Ice Observation Techniques

Comparison of KRMS (top), SAR (middle: C-, L-, and P-bands), and AMMR (bottom: 18 GHz horizontally polarized) data obtained with the NRL P-3 and NASA DC-8 aircraft over a portion of the Beaufort Sea. The AMMR data are observed to delineate the transition from first-year ice off the Alaskan coast to multiyear ice in the central Arctic. The KRMS and SAR imagery correspond to only a small portion of the AMMR trace (approximately 2 minutes of DC-8 flight time). Dark areas in both the KRMS and C-band SAR imagery correspond to first-year ice whereas light areas correspond to multiyear ice types. A comparison of the images shows that C-band provides good discrimination between multiyear and first-year sea ice types, while the longer wavelength P- and L-bands highlight ridges but not ice types. This result is particularly promising for the development of C-band SAR algorithms for use with upcoming spaceborne SAR programs.

study the effects of surface- and volume-scattering from sea ice. Airborne SAR experiments would provide radar sea-ice signatures not only for the development of sea ice classification techniques, but also to gather the data needed for developing ice motion algorithms. These techniques and algorithms are needed in preparation for several upcoming space missions, including ERS-1, Radarsat, and the SIR-C (Shuttle Imaging Radar) Space Shuttle experiments. It is also highly desirable to integrate airborne SARs with other sensors such as multifrequency microwave radiometers and precision multifrequency scatterometers. Combined active/passive microwave signatures may help with current limitations in the determination of ice concentrations during summer months when a large fraction of the polar sea ice is covered with melt ponds.

Further, aircraft programs need to be developed that combine high-resolution, multichannel microwave radiometers with high-resolution, multichannel SAR imagery to allow full utilization of new data sets from the Defense Meteorological Satellite Program's SSM/I, and upcoming data sets from ESA's ERS-1 satellite and the Eos missions.

Synthetic Aperture Radar Techniques. There is a requirement for real-time processing of SAR data and downlink of SAR observations to research vessels operating in ice and open ocean to validate microwave returns. There is also a requirement for wide-swath airborne SARs to support development of ice motion algorithms and ice dynamics theories.

7.3 Snow Studies: The Scientific Challenge

Spaceborne sensors offer an outstanding opportunity to survey snow cover much more extensively than can be done practically from the ground. Satellites instantaneously and repetitively view the snow over large areas. Not only can the sensors reveal when and where snow is present, but they have the potential to monitor many important snowpack properties, such as depth, water equivalent, presence of melting, and the state of the underlying ground. It is possible to monitor these snowpack properties remotely, because electromagnetic radiation emitted, reflected, or scattered by the snow and the snow-covered ground is sensitive to changes in the snowpack properties. But the development of techniques to extract meaningful information about these properties from the electromagnetic signal received by spaceborne sensors is a significant scientific and technological challenge. In order to achieve this goal, airborne sensors are essential.

To identify the snowpack properties that are inherently suitable for remote sensing, measurements have to be made in the visible, near-infrared, thermal infrared, and microwave regions. In each of these bands certain snow characteristics control the radiation received by the sensor.

Visible/near-infrared sensors respond to the intensity of light reflected from the snow. In essence, these sensors sample the albedo of the snow surface. Snow area can be identified and mapped from visible/near-infrared images. However, the albedo of snow due to rough terrain and to various vegetation covers needs further study.

Thermal-infrared sensors respond to the temperature of the snow surface. Snow, like many other materials, is a source of thermal-infrared radiation. The amount of radiation at a given wavelength depends on the temperature and emission characteristics of the source. Snow-crystal size and liquid-water content modulate both the temperature of the snow and its emission characteristics.

Microwave radiometers monitor the microwave radiation emitted naturally by the

target. The emission mechanism is the same as that for thermal infrared radiation. But at microwave wavelengths, the emission characteristics of the material tend to be more important than the temperature for determining the intensity of radiation. A variety of snow characteristics control snow's interaction with microwaves. The microwave signature is influenced by surface and underlying ground emissions. (Emissions by the underlying ground are scattered within the pack and contribute to the signal when the total snow depth is less than 10 to 100 times the wavelength of the microwaves.) Thus, microwave radiometry is potentially a very valuable tool for monitoring snowpack properties. Radar also has potential for surveying snowpacks.

7.4 Snow Studies: Airborne Observational Needs

Near-Infrared Detection and Synthetic Aperture Radar. There is a need to develop a near-infrared detector sensitive to 1.1- to 1.6-m radiances. This region is not sensitive to crystal size variations. Also, an airborne multifrequency/multipolarization SAR should be developed to study the effects of surface and volume scattering from snowpacks; an X-band SAR would be useful for wet snow detection, while development of a K-band SAR would greatly enhance the opportunity to observe surface-snow properties.

Radiometers. High-frequency radiometers (90 and 140 GHz) would be useful for increasing our knowledge of how microwaves are scattered by snow crystals. At these frequencies, many snow and ice properties (and properties of the underlying ground) not detectable in the thermal-infrared region are evident. One of the key areas to which a radiometer sensing these frequencies would contribute is the study of the scattering effect that snow and ice crystals have on the emissions from the underlying ground. Integration of these new sensors on aircraft would be highly desirable for advancing our understanding of such snow properties using remote-sensing techniques.

7.5 Land Ice Studies: The Scientific Challenge

Airborne remote-sensing observations of ice sheets, ice fields, and individual glaciers have brought about important, evolutionary changes in our concepts about their role in the global climate system. Airborne observations of ice thickness, surface elevation, and surface morphology have begun to focus our view of

Snow Survey

NOAA uses three light, twin-engine aircraft to measure snow depth in selected basins covering virtually the entire snow belt of the United States and southern Canada. The aircraft measure gamma radiation from an altitude of 500 feet over specific preselected tracklines. Gamma radiation is a naturally occurring emission from the Earth that is attenuated by water. The measured difference between winter radiation and baseline radiation, determined in snow-free seasons, produces the average inches of water along the trackline. These data are critical for water conservation and control. Aircraft provide the only feasible coverage of the expansive areas that need to be surveyed.

the large ice masses on their interaction with the global climate.

Recent studies of the ice sheets have included the extraction of paleoclimates from deep ice cores and an examination of their role in changing the global sea level. From these studies, several fundamental questions about large ice masses have arisen, including concerns regarding whether the large ice masses are growing or shrinking, what the shapes of the large ice masses are, and what the history of ice movement has been. These questions are central to the study of land ice and define experimental areas in which airborne remote sensing has played, and will continue to play, a critical role.

Key observable parameters associated with the questions above include surface and bedrock topography, accumulation and ablation rates, near-surface temperature, surface velocity, and the location of dynamic features (such as rifts, ice cliffs, and surface and basal crevasses). Aside from dynamically unstable phenomena like glacier surges or ice streams, changes in surface elevation are likely to be small, on the order of 10 cm per year, placing a bound on the accuracy of surface elevation measurements for a specified observation interval. Ongoing and proposed experiments utilizing airborne radar and laser altimeters address this point (see Figure 7-2). Measurements of basal relief using high-frequency (HF) surface and airborne radar technology are currently inadequate for most applications. Minimum annual surface accumulation (the most difficult to measure) is found in East Antarctica and is on the order of 10 cm per year. While this measurement is typically made on the surface via either repeated stake observations or chemical stratigraphy, there is reason to believe such accumulations could be inferred from passive microwave data. Ice velocities range from nearly zero to rates of up to several kilometers per year. Repeat aerial photographic or SAR observations of features moving with the ice, such as crevasses, have been shown useful for estimating surface velocity. Temperatures, as they relate to "proxy" indicators of climate change and to ice flow, are most useful if measured below the level affected by annual swings. Surface temperatures are probably more central to the interpretation of some forms of remote-sensing data and are required at better than 1-degree accuracy.

Airborne ice-penetrating radar studies (radio echo-sounding) have provided nearly our entire view of interior Antarctica and Greenland, yet spatial coverage is woefully sparse. Many parts of the Antarctic continent have no bedrock-topography coverage. There is a significant opportunity to unravel much of the plate-tectonic history of Antarctica through combined ice-radar, aeromagnetic, and airborne gravity studies.

7.6 Land Ice Studies: Airborne Observational Needs

Glaciology Dedicated Aircraft. Advances in HF radar technology (both hardware and software) offer the possibility to significantly improve radio-echo-sounding techniques, to include capabilities for digitizing data and recording both amplitude and phase, as well as variable-frequency, variable-pulsewidth, and variable-beamwidth features. However, other existing equipment such as SARs, scatterometers, Global Positioning System, passive microwave imagers, laser and radar airborne altimeters, and infrared imagers could be profitably used for glaciological research but are not, simply because of the lack of a dedicated platform that could incorporate a suite of instruments for multiple-instrument experiments. Therefore, the most important requirement for the glaciology community is the identification of an aircraft (perhaps a C-130), instrumented with these modern technologies and dedicated to routine use (over at

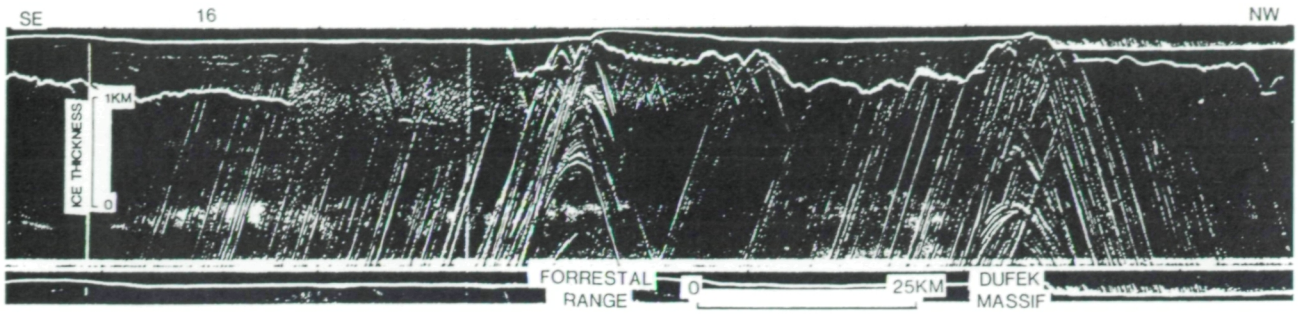

Figure 7-2. Radar Sounding of Glacier Ice

Radio echo ice-sounding profile along line 16 looking southwest. The highest bright reflection is from the ice surface, and the one directly below is from bedrock. Note the diffraction hyperbolas characteristic of the rough surface of the Dufek intrusion, which probably composes the bedrock along the entire profile. The diffraction hyperbolas beneath the ice surface just southeast of the Forrestal Range are caused by crevasses in the Support Force Glacier (Behrendt et. al.: Aeromagnetic Measurements Over Dufek Intrusion).

Shortly after World War II, several military aircraft crashed into the Greenland icecap, and surviving pilots reported that their radar altimeters had indicated altitudes of several thousand feet above the surface. Experiments quickly revealed that glacier ice is relatively transparent to radio waves, so the altimeters were, in effect, reporting the altitude of the airplane above bedrock rather than above the surface of the ice. The misfortune of the military crews became the good fortune of glaciologists and geologists as they set about to deliberately profile the polar glaciers of Greenland and Antarctica.

Before development of airborne, glacier-penetrating radars, the only way to observe ice thickness was from the glacier surface using either seismic reflections (dangerous and logistically complicated) or gravity measurements (very low accuracy of ice thickness determination). Since the radars' development, many thousands of kilometers of flight data have been obtained over Antarctica and Greenland; nearly all of our knowledge of ice volume and bedrock configuration of these areas derives from airborne surveys. From surveys like the one shown above, we understand many of the basic differences between East and West Antarctica crustal structure, for example, and the fact that West Antarctica is actually an archipelago whose bedrock is mostly below sea level.

least a 5-year period) for experiments over the ice sheets. Such a platform should incorporate geophysical instruments (magnetometers, magnetic gradiometers, and gravimeters when possible) for mapping of the subice geology.

7.7 Permafrost Studies: The Scientific Challenge

Permafrost contains a unique, direct record of temperature variations in polar regions because the water in the soil and rock is frozen, so all heat transfer is by conduction. Permafrost, therefore, is a natural laboratory for testing theories of atmospheric temperature increases postulated to have occurred since the increase in "greenhouse" gas concentration following the industrial revolution. But ideal permafrost drilling sites must be situated in areas of uniform and similar fractional ice content. Permafrost studies, therefore, particularly those related to temperature variations, need a collection of synoptic permafrost maps.

7.8 Permafrost Studies: Airborne Observational Needs

Permafrost Mapping. In order to provide permafrost studies with the detailed maps required for the location of drilling studies, airborne electromagnetic methods should be advanced and applied in this area. Promising new technologies include the SAR now flying on the NASA DC-8. Availability of this instrument to the permafrost community would be of great value in mapping efforts.

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Basic Research-Aircraft Systems: Technical Challenges and Needs of Geoscience

8.1 Aircraft Positioning and Navigation Systems

WHEN OBSERVING the solid Earth from an aircraft, it is unfortunately typical for the largest observational errors to result from limitations in aircraft position data. However, compared to the results of a few years ago, positioning-error reduction by a factor of 10 is not unusual for modern airborne observations obtained using state-of-the-art navigation. Therefore, entirely new missions can be flown. Closely spaced trajectories, which would have been navigationally indistinguishable using older instrumentation, can be flown accurately today. Using denser flight lines, richer and more robust data sets can be obtained. Digital recovery of position data, combined with digital recording of flight data, brings powerful new data sets immediately to computers for processing and interpretation.

In atmospheric and oceanic science, we are moving from times when one-dimensional profiles are adequate to a time when two-dimensional profiles are standard. We can expect to move soon to expectations of three-dimensional information, which can be gathered by a single platform using scanning remote sensors or traversing parallel and closely spaced flight lines, or, when simultaneity of observations is crucial, by multiple

Microwave Transponder Navigation

The Environmental Protection Agency sought a geophysical method that could detect steel casings of abandoned wells in old oil fields. A modeling analysis suggested that useful detection and resolution of these small magnetic anomalies required flights less than 300 feet above ground level and flight lines less than 300 feet apart. Using a short-takeoff-and-landing (STOL) aircraft and microwave transponder navigation, data sets were obtained that clearly showed the magnetic anomalies from such wells. Many of the wells that were detected would have been found only at great expense using ground geophysical survey methods; in some cases, access for ground surveys could not have been obtained at all and the wells would have remained undiscovered.

aircraft flying parallel flight lines. In any of these techniques, precise navigation and positioning are just as essential as they are when observing the solid Earth; scientists need reliable position information in order to compare and interpret multiple flight-line data.

It has been noted elsewhere in this report that there is a trend in airborne geoscience toward large, multiagency, multidisciplinary programs. In this context, agencies should consider the navigational needs of the entire user community before settling on a particular approach to new or upgraded navigation systems for its fleet. Agencies should explore ways to enhance navigation-system compatibility between aircraft and between agencies. Some of the modern airborne positioning/navigation systems are discussed below.

8.1.1 Global Positioning System

The most spectacular of the new positioning technologies is the satellite-based Global Positioning System (GPS), a constellation of satellite transmitters that allows relatively simple and inexpensive receivers to immediately determine the position of an aircraft with an accuracy of a few meters. This does not represent the physical measurement limit of the system, however, because more sophisticated receivers and computer processing of GPS receiver data can recover positions with accuracies on the order of 0.1 m from moving platforms. The rapid and simple exploitation of this maximum-resolution capability depends on having access to an encoded transmission from the satellites, called the P-code, which reports the instantaneous positions of the satellites. With P-code, it is possible to navigate in real time with precision on the order of meters or less. Without P-code, it is not possible to navigate in real time with this precision, but position recovery of nearly this accuracy is available after the fact through computer processing of multiple satellite observations and deduction of satellite orbits.

GPS allows entirely new types of measurements to be undertaken. For example, when enough satellites are visible to the receiver, vertical position is obtainable. Absolute altitude, rather than atmospheric pressure altitude, can be used as the reference framework for atmospheric measurements over land as well as over the ocean, where absolute altitude has been previously available only using radar altimetry.

Utilization of GPS depends on having a line of sight to several satellites. The constellation of GPS satellites presently in orbit limits use of the system to certain time windows, particularly in polar regions. However, the Department of Defense plans to deploy a much-enhanced constellation of GPS satellites by 1990.

The advantages of GPS navigation include worldwide coverage with no need for ground facilities, zero drift, and exceptional accuracy. Disadvantages are relative slow update rates, limited time windows, and the need for data postprocessing to obtain maximum precision.

8.1.2 Inertial Navigation Systems (INS)

Inertial navigation has been a standard for long-distance aircraft for many years. Inertial navigation systems are prone to drift (error accumulation) when they are operated over long times or distances, although improvements in electronic and accelerometer technology, such as new laser ring gyros, are reducing INS drift levels. INSs are particularly effective in measuring relatively short-duration accelerations of a platform. Exciting new possibilities exist in the realm of combining GPS and INS technologies. For example, we appear to be on the verge of practical airborne gravity measurements by combining

the short-term capabilities of INSs to measure platform accelerations with the absolute and highly accurate (though relatively slow) GPS updates.

8.1.3 Microwave Transponder Systems

The development of microelectronics has made it possible to place smart, dedicated, sub-meter-resolution microwave navigation systems in aircraft. The systems operate on the principle of sending encoded triggering signals from the aircraft to transponders placed at known ground points, then measuring the combined time of flight of the aircraft transmission and the transponder's response. Aerial coverage is limited by signal strength; it is difficult to increase transponder signals substantially because transponders are normally battery-operated. Typical range capability is several tens of kilometers. The best application for microwave transponder navigation systems, therefore, is limited-area surveys over or near land areas, where flight-path recovery on the order of meters is necessary.

8.2 Aircraft Communications and Telemetry Systems

The communications systems used in airborne geoscience flight programs involve voice and digital signal processing and transmission in varying degrees of sophistication. An ideal voice system permits extended-range, reliable, two-way voice communication between the ground and all of the aircraft flying in the experiment, as well as among the aircraft. An ideal data link provides high-rate, real-, or near-real-time data to and from the ground or among aircraft.

Reliable voice links are an obvious necessity for the safe operation of aircraft, but they are of increasing importance as the spatial scales of experiments increase and aircraft have to fly farther and farther from their operations base. In over-land and coastal flight missions, pilots usually can communicate with a source of weather information even when they are far from the operations base. However, the investigator who needs to communicate with the operations base to replan inflight science operations in reaction to inflight contingencies may not be able to do so. For major, long-range programs, such as the Airborne Antarctic Ozone Experiment, *ad hoc* ground links can be set up, but the investigators in less glamorous long-range experiments usually operate isolated by distance from the operations base.

In ocean science, where long-distance flights over the ocean and away from air traffic control lanes are the norm, voice communication links are of vital importance to both the pilots and the investigators. While the investigator's needs and problems are the same as those described above, pilots flying over remote areas of the ocean often lack basic, up-to-date weather information. In experiments involving links with ships, the ship's communication links with the land can provide information needed by both the pilot and investigators.

Recent advances in satellite communications technology may provide airborne geoscience with the voice links it needs for long-range flight missions over both the land and ocean. Currently, these voice links are of use primarily to pilots; soon, the capacity of these satellites may be more available to investigators for communications with the operations base.

Data links have proved to be valuable to both the pilots and investigators in the Airborne Antarctic Ozone Experiment. Satellite maps of weather systems and the location of the ozone hole were transmitted via ground and satellite communication links to the sci-

ence team at the operations base in Punta Arenas, Chile. These maps were available in near-real time and permitted the investigators and flight specialists to plan each day's flight missions to maximize science return and minimize risks.

Data telemetry links from ground to aircraft and from aircraft to ground are also needed. Data from airborne geoscience sensors and instruments are typically recorded onboard and carried to the ground for analysis. For many experiments, especially those flown on larger aircraft, this approach is sufficient. On smaller aircraft, however, wherein the equipment and passenger complement is limited, onboard processing and experiment operations options are also limited. Without ground-based real-time display of data and instrument operability, experiments flying on such aircraft have to be designed to run on their own and can not be manipulated in flight in the event of a contingency. This has limited the science return on stratospheric chemistry, for example, because this discipline relies on smaller, high- altitude aircraft such as the ER-2. The ability to transmit satellite instrument data (including weather maps), data from oceanborne instruments, and ground-based data sets to inflight aircraft would improve the safety and efficiency of airborne geoscience missions. The ability to perform real-time data analysis on the ground would permit larger payloads and smaller aircraft to fly a greater variety of missions.

Currently, the major drawbacks to the establishment of standardized data links are simply that most flight programs (with the exception of programs like NOAA's yearly hurricane research missions) are not repetitive or permanent enough to warrant "hard-wiring" a system that could then prove to be of limited service. However, in the coming era of ongoing global change experiments with the increased emphasis on spaceborne/airborne sensor interaction, there will be impetus for improvements in this area.

In summary, there is a clear need for improved communication between research aircraft and their operations centers. This need is especially acute for long-range aircraft away from their bases for many hours, and for aircraft operating in hazardous regions where the hazards can be detected and warnings sent from a remote base. Improvements are needed both in two-way voice and digital communication. A two-way digital link would allow weather maps and satellite images to be sent to the aircraft, while airborne *in-situ* and radar data could be returned to the operations base. Satellite links seem especially promising, but other technologies may also prove useful. Communication formats should be designed so that they are compatible between agencies.

8.3 Aircraft Data Systems and Data Management

8.3.1 Aircraft Data Systems

Many modern research aircraft have computer-based data systems that provide the user with control over the activities of the data acquisition process, as well as real-time calculation and display of the data in scientific units during flight. However, the data acquisition and data processing systems for many of the active microwave sensors now flying are antiquated and need to be modernized so that these instruments (and/or their successors) will be viable through the 1990s and beyond. The rapidly advancing technology of smaller and even more powerful computers and associated equipment has made it possible now to develop data systems with vastly improved capabilities. Some of these advances are briefly discussed below.

- ***Physical characteristics:*** The new data systems will be lighter in weight, will be smaller in size, will consume less power than

current systems, and will be more reliable in harsh environments.

- ***Use of color displays:*** High-resolution color displays will allow improved data plots and more information on each screen.
- ***User interfacing:*** Use of windowing software will allow more efficient and logical user interaction. To minimize use of the keyboard, user input will be primarily via a simple directional device, such as arrow keys. Data displays will be flexible and easily customized to user needs.
- ***Advanced hardware and software:*** The availability of aircraft-compatible hard disks and their large storage capacities provides the possibility of vastly increased software capabilities. Together with the much higher speeds of current systems, these hardware capabilities will allow software developments in windowing, in display, in data storage and retrieval, and in the expansion of processing options.
- ***Display updates:*** Larger memory and faster computing capability will allow faster update rates even with multiple displays.
- ***Data storage:*** New cartridge tape and optical disk units offer promise of orders-of-magnitude improvements in data-storage capacity compared to conventional nine-track tape systems.
- ***Data communications:*** As discussed in Section 8.2 above, the new data systems will tie in directly to data telemetry systems transmitting flight-level measurement data from air to ground, as well as other data (radar/satellite images, etc.) from ground to air. Satellite communications links will be used to allow extremely long-range data transfer.
- ***Data turnaround:*** The new data systems will provide for rapid turnaround of airborne measurement data to facilitate the study of a variety of phenomena. Such improvements will significantly enhance our understanding of the factors associated with the provision of this type of data-delivery from advanced spaceborne sensor systems.

The development of advanced research aircraft data systems with features such as those described above will serve to make airborne research projects more efficient, as well as more likely to achieve their objectives.

8.3.2 Aircraft Data Management

There are three major groups of users who have or require access to airborne geoscience data. The first group is the instrument and sensor scientists who typically work onboard the aircraft and monitor in real time or near-real time the quality of the data as they are being obtained from an airborne instrument. The second group of users consists primarily of research scientists who need to access specific data bases in real or near-real time. This user typically uses instrument- or sensor-specific data and will have processing, delivery, and/or display issues to contend with. The last group of users consists of researchers who query directories and catalogs of the various relevant aircraft data. They need a convenient mechanism in place to obtain the specific data they require. It should also be recognized that for maximum scientific productivity, many of these users merge aircraft data with satellite, balloon, and *in-situ* data.

The multidisciplinary nature of the distributed airborne geoscience data base suggests that when and if the data are gathered into a single archive, the user interfaces and protocols should be sufficiently cross-referenced to maximize scientific return. The data management needs of the upcoming Eos era will no doubt require that airborne geoscience data be archived with reference to satellite and ground-based data as well. The multiagency nature of airborne geoscience programs also suggests that agency managers need to reach agreement on how best to use

current data management technologies and how to facilitate the analysis, interpretation, and modeling endeavors of the science community in the years to come.

To serve the airborne geoscience community successfully, the managers of airborne geoscience data will need to interact and interarchive with existing data compilation projects such as NASA's Pilot Climate, Pilot Land, and Pilot Ocean Data Systems.

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Interagency and Agency-User Considerations

9.1 *Interagency Collaborations*

ALTHOUGH the three U.S. Government agencies most concerned with airborne geoscience—NASA, NOAA, and NSF/NCAR—have somewhat different foci in the research aims (as described in Section 3), they often complement each other in fulfilling national and international research objectives, as evidenced by their joint participation in major field projects (see Section 2). The recently concluded expedition to investigate the springtime depletion of ozone in Antarctica is an example of interagency/international cooperation wherein one agency's aircraft (NASA's ER-2 and DC-8) were used to carry instruments supplied by scientists from NASA, NOAA, NSF/NCAR, universities, and industry. The airborne missions were coordinated with satellite, ground-based, and balloon observations, using weather predictions supplied by British scientists. EMEX, FIRE, and STEP are also good examples of cooperative airborne research programs. Interagency coordination of these programs permitted the participating agencies to share data and ground-based scientific facilities.

Another program described in Section 2, GALE, exemplifies a single large program that drew multiagency aircraft (a total of nine) and ground resources from NOAA, NASA, NSF/NCAR, the University of Washington, MIT, and North Carolina State University. A coordinated study of synoptic and mesoscale features atmospheric processes over the Atlantic Ocean was clearly beyond the capability of any one agency, but by pooling resources, a large comprehensive experiment was successfully conducted.

9.2 *Institutional Limitations*

Operational interagency collaboration of the sort described above is generally quite effective. However, in view of the major investments represented by current research aircraft platforms and instrumentation, it is important that steps be taken to optimize the application of these facilities to scientific programs.

Typically, a scientist wishing to utilize an agency's airborne geoscience capabilities must obtain both facility and personnel resources, encountering long lead times for aircraft access. This process, exacerbated by variations in funding from year to year, can serve to restrict projects. Major differences between the NOAA, NASA, and NSF/NCAR flight-facility procedures for the allocation of aircraft can also add to the complexities faced by a researcher in procuring aircraft time. Another factor has been that, historically, the

science community has organized projects devoted to one discipline without the cross-fertilization with other disciplines that could enhance their research. In the past, aircraft programs have often focused on a single subject such as cloud microphysics, boundary-layer chemical fluxes, or cloud chemistry, without realizing the benefits that could be obtained by a multidisciplinary approach. Although the growing view of the geosciences as a unified subject and the maturing of these disciplines will alter the way that research aircraft are used in the future, each of the agencies included in airborne geoscience will continue to have different missions to perform with their aviation facilities. Therefore, it is natural that their procedures and policies related to the use of these facilities may differ. From the standpoint of the user scientist, however, there are several areas where improvements in the interactions among agencies and between agencies and users could be highly beneficial.

9.3 Recommendations for Interagency and Agency-User Cooperation

In examining this general area of interagency and agency-user cooperation, several areas were identified where improvements could be realized, as listed below:

- Facility managers should alert the scientific community to flight opportunities as "piggyback" investigations on research missions where the payload of the aircraft is not used fully by the primary investigators.
- Communications with the university scientific community should be intensified and broadened to convey information on facilities available (platforms, instruments, etc.), flight opportunities, availability of scientific data from previous missions, and contact points where additional information can be obtained. *The Airborne Geoscience Newsletter* and the Airborne Geoscience Workshops should continue to be used to facilitate such communications.
- The Interagency Steering Committee on Airborne Geoscience should meet at regular intervals (approximately quarterly) with an emphasis on developing new areas of collaboration and cooperation among the agencies involved and on improving interactions with the scientific community. Some of the topics that should be explored are as follows:

  - Joint development programs for research instruments
  - Sharing in the use of research instruments
  - Sharing in the use of research aircraft
  - Common formats for data recording and archiving
  - Consistent accounting procedures for charging aircraft usage fees to other agencies
  - University research aircraft
  - Commercial research aircraft

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Recommendations

THE SPECIAL INTERAGENCY Task Group on Airborne Geoscience strongly recommends the developments, acquisitions, and improvements in the technology and organization of airborne geoscience research described in this section. These major recommendations are derived from the needs described previously in this report. These recommendations are *not* listed in priority order; the consensus of the Task Group is that each recommendation is important and should be implemented.

10.1 Airborne Platform Recommendations

The following recommendations in the area of airborne platforms include a variety of platform-related issues, including aircraft development, aircraft acquisition, and the dedication or increased availability of various types of platforms to certain geoscience missions.

A. Large-Payload, Long-Range Aircraft with Low-Altitude Capability. One of the most needed airborne platforms for geoscience is a long-range, large-payload aircraft. The sampling equipment requirements for atmospheric chemistry, the requirement to carry and drop large deployables for ocean science, and the multiple-sensor packages advocated by glaciology and other terrestrial science disciplines all point to a large aircraft of the C-130 type. The requirement for long-range capability is widespread, since it implies not only the ability to fly to distant areas of interest, but also the ability to stay on station for longer periods of time and at lower altitudes, increasing science return and permitting repeat passes over areas of interest. The ocean science community needs access to a C-130-type aircraft with added fuel capacity for this purpose. The glaciology community needs regular access to (or dedication of — see below) a similar aircraft. The Task Group recommends acquisition of an aircraft with a cruise range of approximately 6,000 nautical miles and a full-fuel scientific payload of at least 10,000 lbs.

B. Large-Payload Aircraft with High-Altitude Capability. The terrestrial science community has a need for a large-payload aircraft with the ability to fly at high altitudes (greater than 45,000 feet) for the development of multiple remote-sensor systems. The aircraft would serve the geological and hydrological communities by providing a test platform for the development of sensor and communications systems for potential space deployment and by supporting investigations with unique requirements best served by aircraft. Many of the pressing scientific questions involving the terrestrial sciences, such as the interaction of the biosphere with the hydrosphere and the atmosphere, can not be addressed adequately

with one or two sensor packages, but require information derived from many instruments. The development of an aircraft capability to accommodate simultaneous measurement capability from high altitudes would allow the terrestrial science community a chance to break new research ground and to prepare for the Eos era.

C. Subsonic, Mid-Sized Aircraft with Ultra-High-Altitude Capability. The stratospheric chemistry community has indicated a need for the development of an ultra-high-altitude (70,000 to 100,000 feet) platform capable of flying at subsonic speeds. No such aircraft currently exists. This platform would permit stratospheric chemists to extend the recent advances in stratospheric chemistry gleaned from instrument packages flown on NASA's U-2s and ER-2s to studies of the upper stratosphere. The upper region of the stratosphere contains large vertical gradients of important chemical species, such as ozone, chlorofluorocarbons, sulfur compounds, carbon dioxide, and water vapor. Sampling of these species would require a platform capable of flying at subsonic speeds.

D. Mid-Sized Jet Aircraft with High-Altitude Capability. A mid-sized, high-altitude jet platform is needed to fill the niche between small, high-altitude aircraft such as the U-2 and ER-2, and large, less-high-altitude aircraft such as the DC-8. This platform is needed for a variety of atmospheric studies, including stratosphere-troposphere exchange, storm structure and dynamics, atmospheric chemistry, mesoscale and synoptic meteorology, and cloud physics. For example, this aircraft could be used to perform *in-situ* cirrus and cumulus cloud-top experiments for shortwave radiative-process studies. One of the tasks facing cloud-top radiation studies is the determination of the influence of cloud-top radiative-flux divergence on the development of cloud layers. The platform needed for this type of study must be able to perform repeated penetrations of the tops of cirrus and cumulus clouds in order to study microphysical processes and radiation interactions therein. Rising cumulus cloud tops exceed 10 meters/second, a speed for which a high-performance jet aircraft would be needed. The typical altitude range for cloud tops is 30,000 to 40,000 feet, which is above the ceiling of the P-3 and Electra aircraft. For this type of study, and to serve the atmospheric science community at large, the candidate aircraft should be able to fly a scientific payload of 5,000 lbs. (with full fuel), and should have a range of greater than 4,000 nautical miles, an endurance of greater than 9 hours, and a maximum altitude in excess of 50,000 feet with full payload.

E. Long-Range, Storm-Penetrating Aircraft. Studies of weather system dynamics, cloud microphysics, and cloud electrification all call for the development of a long-range, storm-penetration aircraft. Data regarding precipitation development (particularly the role of ice particles), severe downdrafts and microbursts, and charge-separation mechanisms are sparse because of the need for a specially hardened platform to carry the appropriate suite of instruments into thunderstorm cores. Today there is only one such storm-hardened aircraft available for storm studies—a T-28 flown by the South Dakota School of Mines and Technology. The T-28 was armored and instrumented for hail research in the late 1960s and has been in need of replacement for several years. The ideal replacement would have twin engines offering reliable operation in regions of heavy hail, icing, rain, and lightning; should be hardened against lightning and penetration of large (2-inch diameter) hail; and should be stressed for maneuver loads of +5 to -4 g's. The aircraft should have a research altitude capability of up to 45,000 feet and a flight endurance of 4 to 5 hours.

These requirements point to a ruggedized, military-type aircraft such as an F-15.

10.2 Airborne Instrumentation Recommendations

The following recommendations in the area of airborne instruments are broken down into remote, *in-situ*, and deployable sensors; first we address recommendations that span these areas.

A. Three-Stage Integration Process. A recommendation coming from the tropospheric chemistry community, but which applies to virtually all types of airborne sensors, concerns the process by which instruments are developed and implemented for airborne use. The first stage of instrument development is the ground stage, including laboratory work and field tests prior to test flights. The second, and usually final, stage is the adaptation of the instrument to the aircraft for flight, including mounting, power supply connections, alignments, and test flights. The recommendation for improved integration involves a third stage of development wherein improvements in instrument sensitivity, response time, and size (i.e., miniaturization) are made; and, if necessary, changes to the aircraft's sampling inlets (for certain *in-situ* sensors) or view ports (for certain remote sensors) are also made. These third-stage enhancements could serve to reduce requirements on aircraft power, air conditioning systems, and fuel, permitting the use of smaller aircraft for certain applications, and could increase the science output of experiments through greater efficiencies.

B. STEP Payload Deployment. A recommendation coming from scientists working on stratospheric-tropospheric exchange processes is to further deploy the Stratosphere-Troposphere Exchange Program sensor package for additional meteorological, trace-gas, particulate, and radiation measurements, in a variety of locations. The STEP package is an example of an existing multisensor system with a multidisciplinary mission, designed to be flown on an ER-2 aircraft.

C. Spaceborne Sensor Package Simulation. In the previous "Platform Recommendations" section, we expressed the need for a large, high-altitude aircraft capable of carrying a multisensor, satellite-payload simulation package for use by the terrestrial science community. Such an airborne sensor package is particularly needed to simulate the multidisciplinary science measurements of the Eos program, in order to prepare scientists to best use the types and combinations of data to be generated by the instruments on the Eos polar-orbiting platforms. In this context, the cryospheric community has expressed a particular need for the integration of airborne high-resolution synthetic aperture radars (SARs) with airborne high-resolution multichannel microwave radiometers to enable full utilization of data sets from the upcoming ERS-1 and from the recently launched Defense Meteorological Satellite Program's Special Sensor Microwave Imager (SSM/I).

10.2.1 Remote Sensor Recommendations

A. Airborne Doppler Radar. Doppler radar has been a highly successful application of radar technology to airborne geoscience. The ocean science community has found that side-looking airborne Doppler radars have been able to measure surface wind speed, which has been shown to correlate to sea surface roughness. Ground-based, multiple-Doppler radar systems have been used for many years by atmospheric scientists to study storm-scale velocity structures, and airborne Doppler radars have been flown to areas of interest as a regular practice in recent years. However, current single-beam Doppler radar technol-

ogy requires that an L-shaped pattern be flown around an area of interest (e.g., a storm) in order to measure the 2- and 3-dimensional motions, thereby incurring potentially serious errors in the derived motion field due to temporal changes in the storm dynamics. Dual-beam airborne Doppler radars currently being developed will be able to measure all three motion components simultaneously, during one straight flight track. Development of these systems should be continued as a high-priority effort.

B. Airborne Doppler Lidar. Since airborne Doppler radars use wavelengths that normally give useful signal return only from areas where precipitation is occurring, there is a need for remote-sensing instruments capable of obtaining air velocity measurements in clear air and nonprecipitating clouds. Airborne Doppler lidars, which normally use a laser wavelength of 10.6 micrometers, fulfill this need. An airborne Doppler lidar can measure air motions by detecting Doppler-shifted backscatter from aerosols and cloud droplets, and thus will serve to complement the data from airborne Doppler radars. This instrument would be of particular value to the study of clear-air microscale and mesoscale circulations. Development and system integration of airborne Doppler lidars should continue as a high-priority effort.

C. Airborne Laser Doppler Velocimeter. The mechanical air-motion sensing systems currently in use introduce errors into the air-motion data because of distortion from either the fuselage flow-field or from boom vibration. Laser Doppler velocimetry, a remote-sensing technique, avoids these drawbacks and has the added advantage of not requiring transducer calibrations. Airborne laser Doppler velocimeters require only a small, defogged window for operation, compared to the mechanical devices required for other technologies. As is the case with airborne Doppler radars and lidars, there is a need for further development of this instrument, particularly in the area of intersecting-beam technology, which would provide three-dimensional air motion data.

D. Airborne Lidar Systems. Airborne lidar systems that measure aerosol structure, clouds, moisture profiles, ozone concentration, and atmospheric temperature and pressure have been under development for the last 10-15 years. These instruments are pointed either below the aircraft to study lower tropospheric and boundary-layer phenomena, or above the aircraft to observe upper tropospheric and lower stratospheric chemistry and dynamics. The value of this class of sensors is that atmospheric profiles are obtained nearly instantaneously as the aircraft flies at a constant altitude, thereby providing a two-dimensional snapshot of atmospheric structure along the aircraft flight track. Airborne lidars and laser profilometers are also used in ocean studies to measure wave activity, bathymetry, chlorophyll-a, and other pigment concentrations in the ocean surface layer. Continued development and improvement in airborne lidar systems are recommended as a high-priority sensor development activity.

E. Synthetic Aperture Radar. Since the late 1950s, synthetic aperture radars (SARs) have offered the terrestrial science community a steady flow of intriguing, high-resolution imagery of land surfaces, vegetation cover, sea surface and undersea characteristics, and cryospheric features including snow cover and topography hidden by snow. One of the major scientific challenges facing the terrestrial science community has been the compilation and interpretation of the great variety of data generated by multifrequency/multipolarization SARs. The high-resolution imagery offered by SARs contains detailed

information that must be analyzed and compared with ground-truth data in order to establish state-variable data sets to be used as the basis for eventual near-real-time data analysis. In particular, the most urgent scientific need of the biospheric sciences in the area of airborne research is the accumulation of data on state variables of vegetation communities and their associated environments. This need will be served by a complement of instruments, and not simply a SAR, but SAR studies are an extremely important part of this mission and should be continued on a high-priority basis.

Similarly, the cryospheric science community needs wide-swath airborne SAR data to support a variety of studies, including analysis of the effects of surface- and volume-scattering from snow packs and sea ice, surface snow properties (for which a K-band SAR is needed), sea ice signatures for ice classification, and ice-motion algorithm development. Upcoming cryospheric studies using Shuttle and satellite-borne SARs will rely on the data sets established by airborne SARs; the cryospheric science community requires a greater emphasis on the accumulation of data sets from airborne SARs (and instrument packages including SARs) in order to make use of their spaceborne successors.

Geologists use SARs for a variety of studies, including the evaluation of surface roughness and the determination of the dielectric constants of rocks, unconsolidated rocks, and soils. The lithospheric science community has defined a need for greater access to the multifrequency (L-, C-, and P-band), quadpolarized SAR installed on the NASA/ARC DC-8. In particular, a P-band data set collected at a 70-degree depression angle is needed. Lithospheric scientists expect to make use of the data gathered from Eos and other spaceborne SARs in the 1990s, and like their cryospheric and biospheric counterparts, need to build verified airborne data sets now in order to prepare for the challenge that awaits in the next decade of remote sensing.

An airborne SAR system could also be used to demonstrate the feasibility of quantitative measurements of the velocity of ocean surface currents at high spatial resolution and accuracy. The effects of other surface motions, such as the orbital velocity of waves, the wind wave phase speed, etc., must also be fully understood. This SAR system can also be used to perform more detailed studies of surface waves and to determine the limitations of inferring directional wave spectra from SAR imagery.

F. Microwave Scatterometers. Synthetic aperture radars are currently in use in ocean science as a means of measuring mid-size wave activity and larger sea surface wind perturbations, such as those caused by the presence of an island or ship. Scatterometry is a related technology wherein the scattering effect (backscatter) that sea surface roughness has on transmitted microwaves at oblique angles is measured and used as an indicator of surface wind speed. Ocean scientists emphasize the need for continued development of airborne scatterometers and scatterometry data sets, particularly in combination with other airborne remote and *in-situ* sensors in support of current ocean science and boundary-layer atmospheric studies, and in preparation for the volumes of such data that will be available from spaceborne instruments in the next decade.

G. Visible and Infrared Sensors. The ocean and lithospheric science communities have both expressed needs for improvements in the airborne visible-spectrum and infrared remote-sensing technology available to them. In the visible spectrum, a knowledge of ocean

color is a direct step toward an understanding of marine biological productivity. Prior to 1986, the Coastal Zone Color Scanner (CZCS) aboard the Nimbus-7 satellite provided scientists with these data. Until the next U.S. spaceborne ocean-color sensor flies (probably the Sea-viewing, Wide Field-of-View Sensor [SeaWiFS], aboard the Landsat-6 satellite), airborne ocean-color remote sensors will provide the only means for determining the ocean color over large areas. In the infrared bands, valuable ocean temperature data have been gathered from airborne and spaceborne platforms using a variety of infrared and multispectral remote sensors. Ocean temperature data, when combined with ocean color data, can delineate features such as ocean current and eddies. Airborne sensors of this type provide the ability to cover a specific swath of interest in greater detail than their spaceborne counterparts; continued developments of these sensors for airborne applications are highly recommended.

Lithospheric and hydrologic scientists advocate the further development and application of such instruments as the AVIRIS (Airborne Visible and Infrared Imaging Spectrometer) and TIMS (Thermal Infrared Multispectral Scanner). The AVIRIS is capable of sensing key lithospheric mineral components, nutrient loading in streams and lakes, the spectral albedo of snow and ice, and the spectral signatures of vegetation. It is considered a precursor to the High-Resolution Imaging Spectrometer (HIRIS) that will fly on the Eos polar platform. The spectral range of the TIMS covers the mid-infrared, which is suitable for geologic mapping, especially the identification and differentiation of silicate and nonsilicate rock types. Lithospheric science would benefit from the development and flight of an advanced infrared multispectral scanner to include channels in the lower mid-infrared region (3 to 5 um), which has been insufficiently exploited as a source of geologic data. Cryospheric scientists have a need for the development of near-infrared detectors in the 1.1 to 1.6 micrometer range, wherein snow properties could be measured without the variances caused by crystal size variations. Hydrological scientists have found instruments such as TIMS to be of value in allowing correction for atmospheric variables in surface-temperature measurements, which are of crucial importance to regional estimates of evapotranspiration.

The general finding of the Task Group regarding visible and infrared sensors is that these instruments have proved to be of value to the lithospheric, cryospheric, and hydrospheric communities, and that continued developments are encouraged, with an eye on providing channel coverage to complement existing data. As with all remote sensors destined for space flight, a vigorous program of airborne testing and state variable collection and analysis is crucial to the ultimate benefits to be gleaned.

H. Microwave Radiometers. The microwave emission and absorption characteristics of the Earth's surface, surface coverings, and atmosphere have long been a source of remotely sensed data, including surface and biomass composition, moisture content of biomass and atmosphere, and sea surface salinity, temperature, and wind speed. Microwave radiometers are key components of most air- and spaceborne multisensor packages. One of the needed instruments in airborne geoscience is the dual-channel microwave radiometer. This instrument is capable of detecting and providing simultaneous data in two spectral bands, thereby measuring two temporally correlated but spectrally isolated quantities, such as sea surface temperature and salinity. Atmospheric scientists expect dual-channel microwave

radiometers to be of value in the airborne measurement of path-integrated liquid water, water vapor, and super-cooled water. These measurements would greatly extend their ability to observe cloud parameters. The measurement of these and other cloud parameters is also of great interest in the study of shortwave radiation and other microphysical processes in clouds.

The cryospheric science community has expressed a need for high-frequency (90 and 140 GHz), high-resolution microwave radiometers for snow and ice research. At these frequencies, many snow and ice properties (and properties of the underlying ground) not detectable in the thermal-infrared region are evident. One of the key areas to which a radiometer sensing these frequencies would contribute is the study of the scattering effect that snow and ice crystals have on the emissions from the underlying ground. Such measurements would provide a data set from which important snow and ice properties could be derived.

10.2.2 *In-Situ* Sensor Recommendations

Airborne *in-situ* sensors are used for measuring many atmospheric parameters, such as temperature, concentrations of chemical species, turbulence, and moisture content. *In-situ* sensing from aircraft has reached a more mature level of development than has remote-sensing, and most of the recommendations herein are for incremental improvements in, or continued agency support of, existing technology.

A. Instrument Integration Process. It would be appropriate to reiterate in this section the recommendations given at the beginning of Section 10 regarding the integration of instruments into aircraft. The recommendations for a third stage of instrument integration (i.e., designing instruments and aircraft to be more compatible) came from the tropospheric chemistry community, wherein *in-situ* measurements are a major source of data. One of their recommendations in particular, for improved chemical-sensor inlet systems, is crucial to *in-situ* air sampling and should not be overlooked.

B. Turbulence, Temperature, and Water Vapor Sensors. A detailed and accurate treatment of surface and boundary-layer atmospheric fluxes is essential for improvements in the mesoscale and synoptic-scale models used in operational weather forecasting. Air turbulence sensors, working in concert with temperature, chemical, and humidity sensors, provide data on the motion and turbulent flux of chemical species, heat, and moisture in the atmosphere. Knowledge of these fluxes is essential to studies of chemical species transport (including pollution), convection, weather, and climate. Current *in-situ* turbulence sensors need to be improved in order to remove some of the biases introduced by vibration and aircraft- or boom-related airflow anomalies. The current shortcomings of chemical species and water-vapor probes lie primarily in the area of response time. Faster instrument response would have a significant impact on the ability of scientists to accurately measure fluxes of these quantities. Ongoing support of research and development in these areas is recommended.

C. Water-Vapor Sensors. The measurement of water vapor in the atmosphere remains a problem area for hydrological studies. Current *in-situ* techniques are hampered by slow response time and insufficient sensitivity. The development of radiometric techniques will no doubt supplant *in-situ* techniques in some applications. Radiometric absorption, cryogenic mirror, and other promising methods of advancing the state of water vapor sensing should be vigorously supported.

D. Cloud Physics Sensors. Cloud physics sensors currently form the heart of most airborne atmospheric science programs, and are a necessary component of studies of radiative processes in the atmosphere. The effects of ice and moisture content on reflectance and absorption of incoming solar radiation is one of the key areas of research wherein improvements in the measurement of cloud particulate distribution, ice content, water-vapor content, and liquid-water content would have a significant impact. Another area of cloud physics wherein *in-situ* instrument improvements are needed is cloud electrification. There is a particular need in storm research for improvements in electrical-charge measurement devices, such as field mills, to measure ambient electrical charge in the vicinity of the research aircraft.

10.2.3 Deployable Sensor Recommendations

Sensors deployed from aircraft are used for ocean science and for soundings of atmospheric parameters. Atmospheric data gathered from air-deployable sounders, or dropsondes, are used in almost every subdiscipline within atmospheric science. Ocean science data from air-deployable devices are usually gathered as part of programs that include *in-situ*, ship-based measurements. The aircraft offers the advantage of speed, flexibility, and broad spatial coverage to the ocean scientist who needs to obtain an array of measurements in a certain area.

A. Safe Dropsondes. Currently, no system exists for making safe *in-situ* sounding measurements over land because of the size and weight of the sondes. Tropospheric chemistry, weather system dynamics, and clear-air mesoscale circulation studies would all benefit from the development of a lightweight, frangible sonde that could be deployed safely from aircraft over land. Stratosphere-troposphere exchange and stratospheric chemistry studies would also benefit, particularly if a means of deploying a safe sonde from an ER-2 could be developed for use in stratospheric cloud penetrations. The data that could be gathered from a safe sonde would also be of value to long-wave radiation studies, wherein documentation of the three-dimensional structure of the atmosphere is needed to understand the effect of weather systems on the vertical distribution of long-wave radiation absorption.

B. Expendable Bathythermograph. The ocean science community relies heavily on the Air-Deployable Expendable Bathythermograph (AXBT). The AXBT, developed for use by the U.S. Navy, provides a temperature profile of the upper several hundred meters of the ocean. Its design is driven by the Navy's operational needs, rather than the needs of researchers. The performance characteristics of the AXBT need to be upgraded for research use. The depth range needs to be increased from 305 meters to 1,000 meters; the temperature accuracy needs to be improved from 0.55 degrees to 0.10 degrees C; and the fall rate needs to be increased from 1.5 meters/second to 5.0 meters/second.

C. Expendable Current Profiler and Conductivity-Temperature-Depth Profiler. The Air-Deployable Expendable Current Profiler (AXCP) is a near-surface, current-following drifter that provides ocean scientists with information about ocean current direction and speed. In itself, the AXCP is very useful, but as is the case with any expendable item, it needs to be available essentially off-the-shelf and in great quantities for it to be of real research value. The Air-Deployable Expendable Conductivity-Temperature-Depth Profiler (AXCTD) holds great promise for hydrographic surveys of the upper ocean. With target parameters of a temperature deter-

mination accuracy of 0.03 degrees C, salinity determination accuracy of 0.05 parts per thousand, a fall rate of 3.4 meters/second, and a depth range of 1,000 meters, the AXCTD when fully developed could become the single most important research tool in ocean science in the near future. Its development should be considered a high priority for ocean science.

D. Deployable Optical Sensors. The study of ocean optical properties, which are important keys to the quantification of chlorophyll and other pigment concentrations, would benefit if the newly designed light intensity/temperature profiler (XKT) could be made air-deployable. Additional optical sensors—color and fluorescence profilers, for example—should be developed and made air-deployable for ocean biology and flux studies.

10.3 Positioning Systems Recommendations

The accuracy of the determination and recording of aircraft position is a significant factor affecting the value of data gathered from aircraft. Some types of measurements, such as the gravity measurements used for gathering data about density variations in Earth's crust, are useful only in conjunction with very precise navigation/position data. In some applications, such as the measurement of surface topography (land or sea), the precision of the aircraft altitude data determines the precision of the measurements of interest. In the documentation of all atmospheric flow structures, but particularly in the case of smaller, fast-moving air masses such as storms, accurate three-dimensional position data are key to the usefulness of the measurements made.

The advent of the satellite-based Global Positioning System (GPS) promises to revolutionize those areas of airborne geoscience most reliant on aircraft position data. The tremendous improvement in position data accuracy provided by GPS over current inertial navigation systems (INS) will allow entirely new types of measurements to be made. In terrestrial science, for example, where the mapping of surface features and composition is central to the discipline, post-GPS geological, biomass, and aeromagnetic maps will render their pre-GPS predecessors obsolete by an accuracy factor of as much as 10. Therefore, there will be a general need to compile a new data archive of such maps, and to do so will require access to GPS technology by the various terrestrial and other geoscience disciplines.

Although the evolution to GPS technology will represent a leap forward for airborne geoscience, the transition to GPS will need to be graduated in such a way that data sets incorporating the new, more sophisticated position data are not incompatible with existing data sets. Combinations of GPS and INS technology (e.g., using GPS readings to provide inflight calibration data for an INS) should continue to be explored. Further, agencies engaged in airborne geoscience should explore ways of ensuring position data compatibility not just across the GPS threshold, but also across aircraft and agency interfaces. The approaches to ensuring this compatibility should be decided only after the needs of the user community are determined

10.4 Communications Systems Recommendations

There is a clear need for improved communication between research aircraft and their operations centers. This need is especially acute for long-range aircraft away from their bases for many hours, and for aircraft operating in hazardous regions where the hazards

can be detected, and warnings sent, from a remote base. Improvements are needed both in two-way voice and digital data communications. Two-way data links would allow weather maps and satellite images to be sent to the aircraft, and airborne *in-situ* and radar data to be returned to the base. Satellite links seem especially promising in this area, but other technologies may also prove useful.

Along with efforts to improve two-way data links, agencies should strive for compatible data communication formats. Improved, interagency-compatible, two-way data links would permit a greater amount of real-time data analysis and experiment control from the ground, thereby permitting use of smaller research aircraft, improvement of science return, and shortening of flight times. This need has been expressed in particular by the atmospheric scientists participating in stratospheric-tropospheric exchange studies; they have a specific need for remote inflight control and data links because they often fly their instruments on relatively small, high-altitude aircraft (such as ER-2s) that do not accommodate a scientific crew.

10.5 Data Systems Recommendations

Besides general recommendations for interagency data and data-access protocol compatibility, the major needs expressed during the course of this study came from the terrestrial science community. Partially as a result of the types of experiments carried out in the past, there has not been an emphasis in the terrestrial science community on quick data-turnaround (i.e., in real or near-real time) from airborne missions. Today, the terrestrial science community is studying a greater variety of dynamic processes, including the progress of agricultural crops, the spread of pollution, and the vectors by which diseases (plant or animal) are carried. In addition the cryospheric science community has expressed a particular need for real-time processing of SAR data for transmission to research vessels operating in the highly dynamic ice and open-ocean environment to validate microwave returns. These evolving needs for the quick turnaround of increasingly dynamic airborne data indicate that additional attention should be paid to providing real- and near-real-time data analysis.

10.6 Data Management Recommendations

The three major groups of airborne geoscience data users—the instrument scientists, research scientists, and the ground-based researchers—often merge current airborne data sets with current, or, eventually, archived satellite, balloon, or surface-gathered data. It is therefore imperative that the management of airborne geoscience data ensures that these data can be used in an interactive way and can be interarchived with other data from existing projects such as NASA's Pilot Climate, Pilot Land, and Pilot Ocean Data Systems. It is also important that there be a continual exploration of new technologies for data storage, including such advances as optical disks.

10.7 Interagency and Agency-User Cooperation Recommendations

The need for greater interaction between the various agencies and organizations participating in airborne geoscience, including the user scientists and the university communities, provided the genesis of the Interagency Task Group that has produced this report. It has been a valuable activity, and has led to the identification of the following recommendations for even greater cooperation.

A. Interagency Steering Committee. The Interagency Steering Committee on Airborne Geoscience has been the source of many of the recent advances in interagency and agency-user communications. The Steering Committee should continue to meet and should continue to organize such activities as the Interagency Airborne Geoscience Workshops. Topics that should be addressed by the Steering Committee in the future include joint instrument development, instrument and aircraft sharing, common formats for data recording and archiving, and the development of consistent ways of managing interagency aircraft usage fees.

B. Improved Communications. Communication with the university community should be broadened and intensified to convey information on flight and instrument availabilities and procedures, on the availability of data from ongoing and completed missions, and on points of contact for the pursuit of their airborne geoscience needs. The *Airborne Geoscience Newsletter* is valuable in this context and should be continued.

C. "Piggyback" Opportunities. Facility managers should develop a standard procedure for promptly notifying the science community of opportunities for adjunct investigations on research missions where the payload of the aircraft is not fully used by the primary investigators.

Appendices

OMIT TO END

A.

Appendix A: Typical Annual Flight Activities

FOLDOUT FRAME 1

FOLDOUT FRAME 2

1988-89 Agency Flight Activity Table

Program Mission	Data Type or Sensor	Time Period	Observation Area	Aircraft Type	Aircraft Operator	Principal Investigator Name/Agency	Principal Investigator Telephone
Aeronautical Charting Program	Photos	All Year	U.S.	Aero Comm	NOAA/OAO	FAA/NOS	305 526-7100
Airport Obstruction Program	Photos	All Year	U.S.	Turbo Comm	NOAA/OAO	FAA/NOS	305 526-7100
Atmospheric Processes							
Across Precipitation	Air Chem.	6/88	OH	King Air P3	NOAA/OAO	Boatman/ERL	303 497-6270
Airborne Rain Measurements Rain Radar		10-12/88	VA	T-39	NASA/WFF	Meneghini/GSFC	301 286-9128
Arctic Experiment	Meso	3-4/89	Arctic/Norway	WP-3D	NOAA	Schnell/ERL	303 497-6661
Arctic Ozone	Ozone	1-2/89	Arctic/Norway	DC-8/ER-2	NASA/ARC	Watson/NASA	202 453-1681
Atmospheric Chemistry	Air Chem.	6/88	AK	Electra	NASA/WFF	Hoell/LaRC	
Atmospheric Mapping	MAMS	1, 2, 4, 8/89	CA, VA, FL	ER-2	NASA/ARC	Jedlovec/MSFC	205 544-5695
Convection Waves	Mesoscale	12/87, 4/88	U.S.	Sabreliner	NCAR	Kuettner/NSF	303 491-8293
Convection Waves	Mesoscale	4-5/88	U.S.	King Air	U. Wy.	Kuettner/NSF	303 497-8690
COPS	Mesoscale	5/89	OK	WP-3D	NOAA	Jorgensen/ERL	303 497-6246
ERICA	Mesoscale	12/88-2/89	ME	WP-3D	NOAA	Kreitzburg/Drexel	215 895-2720
GLOBE	Lidar	10/89	Pacific Rim	DC-8	NASA/MSFC	Fitzjarrald	205 544-1651
Hailswath II	Cloud Physics	6-8/89	ND	WP-3D	NOAA	Reinking/ERL	303 497-6167
Ionospheric Optical Physics	Ionosonde	All Year	Arctic & Mid-LATS.	NKC-135	USAF	Webber/AFGL	617 377-3121
IR Imaging	IR	All Year	Various	NKC-135	USAF	Sandford/AFGL	617 377-3370
Marine Boundary Layer	AIR DYN	2-3/88	Miami	WP-3D	NOAA	Hanson/CIRES	303 492-1227
Moisture Source	AIR DYN	2-3/88	Miami/Gulf	WP-3D	NOAA	Lewis/NSSL	FTS 736-3408
Pressure-Temperature Lidar Development	Lidar	4-5/89	VA	Electra	NASA/WFF	Korb/GSFC	301 286-6233
Regional Acid Deposition Model	Trace Gases	8-10/88, 4/89	U.S.	King Air	NOAA/OAO	Boatman/ERL	303 497-6270
REME	Air Chem.	3-4/89	PA	King Air	NOAA	Boatman/ERL	303 497-6270
Snow Shading Boundary L. (SSBLIM)	Boundary Layer	2-3/88	U.S.	King Air	NCAR	Segal/NSF	303 491-8293
Software Instrumentation Intercomparison	Atmos S/W	8-9/89	Wallops/Brazil	Electra	NASA/WFF	Hoell/LaRC	804 865-4779
S. Hemisphere Infrared Exp. (SHIRE)	Atm. Chem.	10-11/88	S. America	Sabreliner	NCAR	Mankin/Coffey/NSF	303 497-1403
Stratospheric Aerosols	Lidar	9/89	U.S.	Electra	NASA/WFF	McCormick/LRC	804 865-2065
Sulphur Measurements	Atm. Chem.	8/88	E. Colorado	King Air	NCAR	Kok/NCAR	303 497-1070
Tropospheric Trace Gases (3CPO)	Atm. Chem.	5-6/88	Central Illinois	Sabreliner	NCAR	Dickerson/U.MD	301 454-5084
Water-Vapor Lidar Development	Lidar	5-6/89	VA	Electra	WFF	Browell/LaRC	804 865-2576
Commercialization/Applications							
Commercial Fishing	AOCI	5-6/89	IL	ER-2		Wrigley	
Ice Mapping	TMS, RC10, AVIRIS	5-6/89	ME	ER-2		Mourad	
Cosmic Dust	Particles	8/88	CA	ER-2/U-2	NASA/ARC	Zolensky/JSC Hoell/LaRC	713 483-3274 804 865-4779
Flight Programs							
Hurricane Reconnaissance	Winds	6-11/88 & 89	Atlantic	WP-3D	NOAA/OAO	Sheets	305 666-4612
Hurricane Research							
Atm. & Ocean Boundary Dynamics	MW, IR, RDR	7-10/88 & 89	Coastal U.S.	WP-3D	NOAA	Black/NOAA	305 361-4320
Inner Core Studies	MW, IR, RDR	7-10/88 & 89	Coastal U.S.	WP-3D	NOAA	Marks/NOAA	305 361-4321
Motion & Internal Dynamics	MW, IR, RDR	7-10/88 & 89	Coastal U.S.	WP-3D	NOAA	Willoughby/NOAA	305 361-4407
Structure of Rain Bands	MW, IR, RDR	7-10/88 & 89	Coastal U.S.	WP-3D	NOAA	Gamache/NOAA	305 361-4437
Synoptic Scale Flow	MW, IR, RDR	7-10/88 & 89	Coastal U.S.	WP-3D	NOAA	Burpee/NOAA	305 361-4502
Land Processes							
Agric. Field Emissions	SAR/L/C/P	9/89	CA	DC-8	NASA/ARC	Wang/GSFC	301 286-8949
Anal. of Ultramafic Terrain	AVIRIS/TIMS	7/89	NV/AZ	ER-2	NASA/ARC	Abrams/JPL	818 354-0937
AVIRIS Data Eval. and Tech. Assessment	AVIRIS	5-9/89	CA, VA	ER-2	NASA/ARC	Wickland/NASA	202 453-1720
AVIRIS Field Calib.	AVIRIS	9/89	CA	ER-2	NASA/ARC	Vane/JPL	818 354-2851
Forest Applications	SAR	9/89	OR	DC-8	NASA/ARC	Zebker/JPL	818 354-8780
Forest Ecosystem	NS001, ASAS	8/89	ME	C-130	NASA/ARC	Smith/GSFC	301 286-7282
Forest Ecosystem Dyn I	SAR	8/89	MN	DC-8	NASA/ARC	Smith/GSFC	301 286-7283
Geologic Surfaces	SAR (L, C, P)	8/89	CA, ID	DC-8	NASA/ARC	Evans/JPL	Not Available
Geomorphic Indicator	AVIRIS	7/89	CA, AZ	ER-2	NASA/ARC	Farr/JPL	818-354-2418
LIMEX/Icebergs & Vessel Detection	SLAR	3/89	Canada East Coast	HU-25/HC-130	USCG/IIP	Osmer/IIP	203 441-2631
LIMEX/Icebergs & Vessel Detection	APS504 Search Radar	3/89	Canada East Coast	H-200	Private Sector	Rudkin/Atlantic Airways	709 576-1204
LIMEX/Ice Signatures	SAR (C,X) C-Scatt Laser Profiler Air Photo	3/89	Canada East Coast	CV-580	CCRS	Livingstone/CCRS	613 998-9060
LIMEX/Ice Surface Roughness	Laser Profiler	3/89	Canada East Coast	Electra	AES	Mudry/AES	613 995-6730
LIMEX/Large Area Event Monitoring	SLAR	3/89	Canada East Coast	Electra	AES	Mullane/AES McNutt/CCRS	613 996-7121 613 998-5916
LIMEX/Large Scale Ice Phenomena	SAR (C,X)	3/89	Canada East Coast	CV-580	CCRS	McNutt/CCRS	613 998-5916
LIMEX/Mesoscale Phenomena	SAR (C,X)	3/89	Canada East Coast	CV-580	CCRS	Ikeda/BIO	902 426-3142
LIMEX/Microwave Investigations	AIMR SLAR Air Photo	3/89	Canada East Coast	Electra	AES	Ranseier/AES	416 739-4685
LIMEX/Oceanic Features	SLAR	3/89	Canada East Coast	HU-25/HC-130	USCG/IIP	Murphy/IIP	203 441-2631
LIMEX/Waves in Ice	SAR (C,X)	3/89	Canada East Coast	CV-580	CCRS	Vachon/CCRS	613 998-9060
Magellan Project	SAR (L), Photo	8/89	ID, CA	DC-8	NASA/ARC	Wall/JPL	818 354-7424
Manganese Cycle	AOCI	8/89	VA	ER-2	NASA/ARC	Wrigley/Nealson/ARC	415 694-6060
National Aerial Photography Program (NAPP)	Aerial Mapping Camera	All Year	U.S.	Lear Jet	Contractors	Light/USGS	703 648-5106
Quantitative Volcanology & Neotechtonics	SLAR	3/89	AZ	T-39	NASA/WFF	Garvin/GSFC	301 286-6565
SLAR Terrain Applications	SLAR (X-hh)	All Year	U.S.	Various	Contractors	Jones/USGS	703 648-4138
Snow Survey	Gamma Rad	Winter	Northern U.S.	AC 500	NOAA	NOAA/NWS	305 526-7100
Volcanic Evolution	TIMS, NS001, Photo	8-9/89	OR, WA, CA	C-130	NASA/ARC	Kahle/JPL	818 354-7265
Volcanic Features	TIMS, AIS, Photo	8/89	CA	C-130	NASA/ARC	Pieri/JPL	818 354-6299
Life Sciences							
Biomass Combustion	TMS, RC10	5-8/89	CA	ER-2	NASA/ARC	Brass/ARC	415 694-5232
Biomass Combustion	NS001, Photo	5-6/89	CA, AZ	C-130	NASA/ARC	Brass/ARC	415-694-5232
Biospheric Monitoring	TMS, CIR, AVIRIS	4-9/89	CA, Mexico	ER-2	NASA/ARC	Sebasta/Wood/ARC	415 694-6060
Coniferous Forests	TMS, AVIRIS, CIR	3, 4, 8/89	CA, OR	ER-2	NASA/ARC	Spanner/ARC	Not Available
Turtle Survey	Visual	6/88-5/89	MS	DHC-6	NOAA	NOAA/NMF	305 526-7100
Ocean Processes							
Global Ocean Flux	Lidar, Radar	4-6/89	North Atlantic	P-3	WFF	Hoge/WFF	804 824-1567
Iceberg Reconnaissance and Research	SLAR	3-9/88	North Atlantic	C-130	USCG/IIP	Osmer/IIP	203 441-2631
Wave Measurements Surface Contour Radar		1/89	VA	P-3	WFF	Walsh/WFF	804 824-1515

*AVIRIS missions resumed in September after resolution of technical problems.

KEY

AFGL	— Air Force Geophysics Lab
AIS	— Airborne Imaging Spectrometer
AOCI	— Advanced Ocean Color Instrument
AOML	— Atlantic Ocean Meteorological Lab
ARC	— Ames Research Center
ASAS	— Advanced Solid-State Array Sensor
AVHRR	— Advanced Very High Resolution Radiometer
AVIRIS	— Airborne Visible & Infrared Imaging Spectrometer
AMSCAT	— Km Band Scatterometer
CIR	— Color Infrared Camera
CLS	— Cloud Lidar System
COPS	— Cooperative Oklahoma P-3 Studies
CRREL	— Cold Regions Research and Engineering Laboratory
CZCS	— Coastal Zone Color Scanner
ERICA	— Experiment on Rapidly Intensifying Cyclones in the Atlantic
ERL	— Electromagnetic Radiation Lab
ERS-1	— Earth Resources Satellite
GSFC	— Goddard Space Flight Center
HIS	— High Resolution Interferometer Sounder
HMS	— High Altitude Multispectral Scanner
IIP	— International Ice Patrol
IR	— Infrared
ISCCP	— International Satellite Cloud Climatology Project
ISLSCP	— International Satellite Land Surface Climatology Project
JPL	— Jet Propulsion Laboratory
JSC	— Johnson Space Center
LRC	— Langley Research Center
MAMS	— Multispectral Atmospheric Mapping Sensor
MCR	— Multichannel Cloud Radiometer
MSFC	— Marshall Space Flight Center
MW	— Microwave
NCAR	— National Center for Atmospheric Research
NHC	— National Hurricane Center
NOS	— National Ocean Service
NSF	— National Science Foundation
NSSL	— National Severe Storm Laboratory
NS001	— 8-Channel Thematic Mapper Simulator
NWS	— National Weather Service
OAO	— Office of Aircraft Operations
PBMR	— Pushbroom Microwave Radiometer
RDR	— Radar
SAR	— Synthetic Aperture Radar
SLAP	— Shuttle Laser Altimeter Prototype
SLAR	— Side-Looking Airborne Radar
TIMS	— Thermal Infrared Multispectral Scanner
TMS	— Thematic Mapper Simulator
TSP	— Tracking Sun Photometer
USCG	— United States Coast Guard
WFF	— Wallops Flight Facility

Appendix B: Performance Characteristics and Instrumentation

B-1. NCAR Aircraft
B-2. NASA Aircraft
B-3. NOAA Aircraft

B-1.

NCAR Research Aircraft Performance Characteristics and Instrumentation

TYPICAL LIST OF PARAMETER MEASUREMENTS AVAILABLE ON THE NCAR AIRCRAFT

Parameter Name	Symbol
RAW INS Latidude (deg)	ALAT
Raw INS Longitude (deg)	ALON
Aircraft Pitch Attitude Angle (deg)	PITCH
Aircraft Roll Attitude Angle (deg	ROLL
Raw Dynamic Pressure (Wing) (mb)	QCW
Raw Static Pressure (Wing) (mb)	PSW
Raw Static Pressure (Fuselage Digital) (mb)	PSFD
Raw Total Temperature (Radome Rosemount) (°C)	TTR
Dew/Frost Point Temp (Top) (°C)	DPT
Dew/Frost Point Temp (Bottom) (°C)	DPB
Raw Lyman-alpha Hygrometer Output (V dc)	VLA
Raw J-W Liquid Water Content (g/m^3)	XLWC
Raw PMS-King Liquid Water (g/m^3)	PLWC
Downward SW Irradiance (WG-7) ($Watts/m^2$)	SWT
Upward SW Irradiance (WG-7) ($Watts/m^2$)	SWB
Angle of Attack (Gust Probe) (deg) (radome)	AKRD
Angle of Sideslip (Gust Probe) (deg) (radome)	SSRD
Corrected Dynamic Pressure (Wing) (mb)	QCWC
Corrected Dynamic Pressure (Radome) (mb)	QCRC
Corrected Static Pressue (Wing) (mb)	PSWC
Corrected Static Pressure (Fuselage, Digital) (mb)	PSFDC
NACA Pressure Altitude (m)	PALT
Ambient Temperature (Radome Rosemount) (°C)	ATR
Ambient Temperature (Wing Deiced Rosemount) (°C)	ATWH
Aircraft True Airspeed (Wing) (m/s)	TASW
Aircraft True Airspeed (Boom) (m/s)	TASR
Dew Point Temperature (°C), Corrected	DPXC
Absolute Humidity (g/m^3)	RHOTD
Corrected J-W Liquid Water Content (g/m^3)	XLWCC
Corrected Downward IR Irradiance ($watts/m^2$)	IRTC
Corrected Upward IR Irradiance ($watts/m^2$)	IRBC
Wind Vector East Gust Component (m/s)	UI
Wind Vector North Gust Component (m/s)	VI
Wind Vector Vertical Gust Component (m/s)	WI
Wind Vector Longitudinal Gust Component (m/s)	UX
Wind Vector Latgeral Gust Component (m/s)	VY
Horizontal Wind Direction (deg)	WD
Horizontal Wind Speed (m/s)	WS
Distance East of Start (km)	DEI
Distance North of Start (km)	DNI
Damped Aircraft Vertical Velocity (m/s)	WP3
Mixing Ratio (g/kg)	MR
Icing Detector (V dc)	RICE
Potential Temperature (°K)	THETA
Equivalent Potential Temperature (°K)	THETAE
Relative Humidity (%)	RHUM
Specific Humidity (g/kg)	SPHUM
Virtual Temperature (°C)	TVIR
Virtual Potential Temperature (°K)	THETAV

(Note: PMS-probe derived parameters such as: concentrations, histograms, dispersion factor, liquid water content, reflectivity, etc. are also available in real time.)

NCAR Aircraft Specifications (1 of 3)

Electra (L-188C)

Description:	Crew:	Two Pilots + Flt. Engineer + 16 Seats Available for Project Participants
	Length:	32.0 m; Wingspan: 30.2 m
	Gross Weight:	116,000 lbs max.
	Engines:	Four Allison 501-D13, 4000 SHP each
	Base:	Jefferson County Airport, Broomfield, Colorado
Performance:	Altitude:	28,400 ft. (operating)
	Range:	2,400 n mi (at 22,000 ft. cruise)
	Endurance:	8.5 hrs max. with IFR reserves
	Speed:	310 KTAS (typical cruise)
	Payload:	20,800 lbs max.; 7,200 lbs with full fuel

Sensors:

Atmospheric State Parameters
Gustprobe Instrumentation for Turbulent Flux Measurements
Cloud Physics Instrumentation
Radiometers (Short-Longwave and Ultraviolet)
Remote Radiometric Surface Temperature
Video Photography
Dropwindsonde Dispensing-Acquisition
Oceanographic Dropsonde Dispensing-Acquisition
LIDAR-Vertical Profiles of Aerosols and Clouds
Atmospheric Trace Gas Sampling

Applications:

Multi-Investigator Experiments Requiring Large Payloads
Measurements in Remote Regions Requiring Long Ranges
Boundary-Layer Studies, Turbulence/Flux Measurements
Oceanographic Investigations
Air-Sea Interaction Measurements
Cloud Physics Studies
Tropospheric Profiling
Radiometric Measurements, Satellite Ground Truth
Atmospheric Chemistry Measurements
Aerosol Measurements

Chronology:

Manufactured in 1959
Acquired by NCAR in 1972

NCAR Aircraft Specifications (2 of 3)

King Air (B200T)

Description:	Crew:	One Pilot + 2 to 3 Seats Available for Project Participants
	Length:	13.4 m; Wingspan: 17.4 m
	Gross Weight:	14,000 lbs max.
	Engines:	Two Pratt and Whitney PT6-42
	Base:	Jefferson County Airport, Broomfield, Colorado
Performance:	Altitude:	33,000 ft. (max.)
	Range:	1,800 n mi (at 33,000 ft. cruise)
	Endurance:	7.3 hrs max. with IFR reserves
	Speed:	240 KTAS (typical cruise)
	Payload:	2,350 lbs max.; 1,680 lbs with full fuel

Sensors:

Atmospheric State Parameters
Gustprobe Instrumentation for Turbulent Flux Measurements
Cloud Physics Instrumentation
Radiometers (Short-Longwave and Ultraviolet)
Remote Radiometric Surface Temperature
Video Photography
Dropwindsonde Dispensing-Acquisition
Oceanographic Dropsonde Dispensing-Acquisition
Atmospheric Trace Gas Sampling
Electric Field Strength Sensing

Applications:

Boundary-Layer Studies, Turbulence/Flux Measurements
Oceanographic Investigations
Air-Sea Interaction Measurements
Cloud Physics Studies
Tropospheric Profiling
Radiometric Measurements, Satellite Ground Truth
Atmospheric Chemistry Measurements
Aerosol Measurements

Chronology:

Manufactured in 1982
Acquired by NCAR in 1982

NCAR Aircraft Specifications (3 of 3)

Sabreliner (NA265-60)

Description:	Crew:	Two Pilots + 2 to 4 Seats Available for Project Participants
	Length:	14.6 m; Wingspan: 13.7 m
	Gross Weight:	20,000 lbs max.
	Engines:	Two Pratt and Whitney JT12A-8
	Base:	Jefferson County Airport, Broomfield, Colorado
Performance:	Altitude:	43,000 ft. (max.)
	Range:	1,300 n mi (at 37,000 ft. cruise)
	Endurance:	3.5 hrs max. with IFR reserves
	Speed:	400 KTAS (typical cruise)
	Payload:	2,050 lbs max.; 1,628 lbs with full fuel

Sensors:

Atmospheric State Parameters
Gustprobe Instrumentation for Turbulent Flux Measurements
Cloud Physics Instrumentation
Radiometers (Short-Longwave and Ultraviolet)
Remote Radiometric Surface Temperature
Video Photography
Dropwindsonde Dispensing-Acquisition
Atmospheric Trace Gas Sampling

Applications:

Upper Tropospheric Dynamic Studies
Stratospheric-Tropospheric Exchange Measurements
Cloud Physics Studies
Tropospheric Profiling
Radiometric Measurements, Satellite Ground Truth
Atmospheric Chemistry Measurements
Aerosol Measurements

Chronology:

Manufactured in 1968
Acquired by NCAR in 1968

NCAR Aircraft Instrumentation

(E = Electra, S = Sabreliner, K = King Air)

VARIABLE MEASURED	AIRCRAFT	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Aircraft Latitude (ALAT)	E, S, K	Inertial Navigation System	Litton LTN-51	±90°	≤1.0 n mi per flt. hr	0.0014°
Aircraft Longitude (ALON)	E, S, K	Inertial Navigation System	Litton LTN-51	±180°	≤1.0 n mi per flt. hr	0.0014°
Aircraft Latitude (CLAT, CLON)	E, S, K	LORAN-C System*	Advanced Navigation Inc. ANI-7000	±90° ±180°	0.19 km (location dependent)	0.0002°
Aircraft Position (DLAT, DLON)	E, S, K	Distance Measuring* Equipment (DME) (slant range)	King Radio, KDM 7000 DME	0+240 km (altitude dependent)	Geometry & Reception Dependent	0.0002°
Aircraft Ground Speed (XVI, YVI)	E, S, K	Inertial Navigation System	Litton LTN-51	0 to 400 m/s	<1.0 knot per flt. hr	0.04 m/s
Aircraft Vertical Volocity (VZI)	E, S, K	Inertial Navigation System	Litton LTN-51	±200 m/s	±0.10 m/s	0.012 m/s
Aircraft True Heading (THI)	E, S, K	Inertial Navigation System	Litton LTN-51	0 to 360°	±0.05°	0.00275°
Aircraft Pitch Angle (PITCH)	E, S, K	Inertial Navigation Resolver	Litton APD 917055	45°	±0.05°	0.00275°
Aircraft Roll Angle (ROLL)	E, S, K	Inertial Navigation Resolver	Litton APD 917055	45°	±0.05°	0.00275°
Inertial Platform Heading (PHDG)	E, S, K	Inertial Navigation Resolver	Litton APD 917055	45°	±0.05°	0.00275°

*Not worldwide coverage.

NCAR Aircraft Instrumentation

(E = Electra, S = Sabreliner, K = King Air)

VARIABLE MEASURED	AIRCRAFT	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Static Pressure (wing - PSW)	E, K	Variable Capacitance	Rosemount Inc 1201F	250 to 1035 mb	±1 mb*	0.07 mb
Static Pressure (cabin - PCAB)	E, S, K	Variable Capacitance	Rosemount Inc 1201F	600 to 1035 mb	±1 mb*	0.07 mb
Static Pressure (fuselage - PSFD)	E, S, K	Oscillation Frequency (digital output)	Rosemount Inc 1501	250 to 1035 mb	±1 mb	0.034 mb
Indicated Airspeed (QCW, QCF, QCR)	E, S, K	Variable Capacitance	Rosemount Inc 1221	0 to 125 mb	0.7 mb	0.006 mb
Total Air Temp. (Rev. flow - TTR, TTF)	E, K	Platinum Resistance Platinum Resistance	Rosemount Inc 102E2AL NCAR built	-60 to 40°C	±0.5°C	0.006°C
Total Air Temp. (deiced - TTWH, TTFH)	E, K, S	Platinum Resistance	Rosemount Inc 102DB, 102CV	-60 to 40°C	±1.0°C	0.006°C
Total Air Temp. (K-probe - TTKP)	E, K	Platinum Resistance	NCAR Developed	-60 to 40°C	±0.05°C	0.006°C

*Assuming transducer is exposed to <1°C/min rate of temperature change.

NCAR Aircraft Instrumentation

*If Relative Humidity is >11%.
**With periodic baselining.

(E = Electra, S = Sabreliner, K = King Air)

VARIABLE MEASURED	AIRCRAFT	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Dew-Point Temp. (DPB)	E, S, K	Thermoelectric Hygrometer	EG&G 137-C3-S3	-50 to +50°C	±0.5°C>0°C* ±1.0°C<0°C	0.006°C
Dew-Point Temp. (DPB)	E, S, K	Thermoelectric Hygrometer	General Eastern Model 1011B	-65 to +50°C	±0.5°C>0°C ±1.0°C<0°C	0.006°C
Crogenic Frost Hygrometer (DPCRC)	S	Cryogenically Cooled Mirror	NCAR Developed	-90 to -10°C		0.05°C
Absolute Humidity (VLA)	E, S, K	Lyman-alpha Hygrometer	NCAR Developed LA-3	0.1 to 25 g/m^3	+5%**	0.2%
Angle of Attack (ADIFR)	E, S, K	Flow Angle Sensor, Radome	Rosemount Inc 1221	±10°	±.17°	0.002°C
Angle of Sideslip (BDIFR)	E, S, K	Flow Angle Sensor, Radome	Rosemount Inc 1221	±5°	±.17°	0.002°C
Angle of Attack (Differential Pressure - AKDF)	S	Flow Angle Sensor	Rosemount Inc 858AJ	±10°	±0.35°	0.004°C
Angle of Sideslip (Differential Pressure - SSDF)	S	Flow Angle Sensor	Rosemount Inc 858AJ	±10°	±0.35°	0.004°C
Radiometric Surface Temperature (RSTB)	E, S, K	Bolometric Radiometer	Barnes Engr. Co. Optitherm	-29 to +75°C	±1.0°C	0.005°C

(1) Degradation of accuracies of certain sensors can be expected when flying through visible moisture or under icing conditions with certain sensors.

NCAR Aircraft Instrumentation

(E = Electra, S = Sabreliner, K = King Air)

VARIABLE MEASURED	AIRCRAFT	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Infrared Radiation (IRT, IRB)	E, S, K	Pyrgeometer 4 to 45 μm (Silicon Dome)	Eppley PIR	0 to 600 W/m^2	----	0.40 W/m^2
Visible Radiation (SWT, SWB)	E, S, K	Pyranometer .285 to 2.800 μm (Clear Dome WG7)	Eppley PSP	0 to 1500 W/m^2	----	0.12 W/m^2
Ultraviolet Radiation (UVT, UVB)	E, S, K	Photometer .295 to .385 μm	Eppley TUVR	0 to 200 W/m^2	----	0.12 W/m^2
Ozone Monitor (TEO3C)	E, S, K	UV Photometer	Thermo Electron Model 49	0 to 1 ppm	4 ppb	1 ppb
Carbon Monoxide (CO)	E, S, K	Gas Filter Correlation Spectrometer	NCAR Developed 1989	0 to 5 ppm	20 ppb	10 ppb
Aerosol Concentrations (CONCNC)	E, S, K	Butanol Condensation Nuclei	TSI Model 3760	0 to 10^5 ct/cm^3	±3% (reading)	1 ct/cm^3

NCAR Aircraft Instrumentation

VARIABLE MEASURED	AIRCRAFT	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Geometric Altitude (HGM)	E, S, K	Radio Altimeter	Collins ALT-55	0 to 762 m	0 to 152 m ±.6 or 2%, 152 to 762m ±3%	0.1 m
Geometric Altitude (HGME)	E, S, K	Radar Altimeter	Stewart-Warner APN-159	0 to 21,000 m	±9.7 m	0.1 m
Cloud Liquid Water Content (XLWC)	E, K	Hot-wire	Johnson-Williams LWH	0 to 5 g/m^3	----	0.005 g/m^3
Cloud Liquid Water Content (PLWC)	E, K	Heated-wire	PMS-CSIRO King Probe	0 to 3 g/m^3	----	0.006 g/m^3
Ice Detector (RICE)	E, S, K	Accretion of Cloud Droplets	Rosemount Inc 871F	0 to 0.5 mm increments	----	0.0005 mm
Photography	E, S, K	VHS Video Cameras: Forward looking, B&W, PULNIX: Model TM-34K Left side, color, GE camera: Model 1CVK 5032A Images recorded on GE Model 1CVK 5022X VCR.			Up to 6 hours of recording (w/wo voice per cassette.)	
Ocean Temperature* (Vertical Profile) (AXBT)	E, K	Airborne Expendable Bathythermograph	Sippican Ocean Systems Inc.	Ocean surface to 760m depth	±0.2°C	0.006°C
Air Temperature* (ATOPH, UVB)	E, S, K	Radiometric Thermometer	OPHIR Model ASSTR-1	-30 to +30°C	±0.5°C	0.05°C
Electric Field* (FM)	E, K	Rotating Shutter Electric Field Meter	New Mexico Tech Model E100			

*Available through special arrangements.

NCAR Aircraft Instrumentation

(E = Electra, S = Sabreliner, K = King Air)

VARIABLE MEASURED	AIRCRAFT	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Aerosol Spectrum (ASASP)	E, K	Laser Spectrometer	Particle Measuring Systems, Inc.	0.12 to 3.12 μm	----	0.025 to -.375μm (progressively weighted)
Cloud Droplet Spectrum (FSSP)	E, S, K	Laser Spectrometer	Particle Measuring Systems, Inc.	0.5 to 47 μm	----	Selectable 0.5, 1, 2, 3 μm
Cloud Droplet Spectrum (260X)	E, S, K	Laser Spectrometer	Particle Measuring Systems, Inc.	40 to 620 μm	----	10 μm
Cloud Droplet Spectrum (200X)	E, S, K	Laser Spectrometer	Particle Measuring Systems, Inc.	40 to 280 μm	----	20 μm
Hydrometeor Spectrum (200Y)	E, S, K	Laser Spectrometer	Particle Measuring Systems, Inc.	300 to 4,500 μm	----	300 μm
Cloud Particle Spectrum (2D) (2D-C)	E, S, K	Laser Spectrometer	Particle Measuring Systems, Inc.	25 to 800 μm	----	25 μm
Hydrometeor Spectrum (2D-P)	E, S, K	Laser Spectrometer	Particle Measuring Systems, Inc.	200 to 6,400 μm	----	200 μm

B-2.

NASA Research Aircraft Performance Characteristics and Instrumentation

NASA Research Aircraft Typical Performance Characteristics

Aircraft	*Manufacturer*	*Model*	*Altitude (Feet)*	*Range (Miles)*	*Endurance (Hours)*	*Payload Wt.*	*Payload Power (kW)*	*NASA Center*
ER-2	Lockheed	- -	70,000	3,200	7.0	2,700	- -	ARC
C-130	Lockheed	NC-130B	24,000	2,000	7.0	20,000	26.0+	ARC
DC-8	MACDAC	72	40,000	6,000	12.0	30,000	80.0	ARC
Electra	Lockheed	L-188	25,000	2,000	7.5	19,000	40.0	WFF
P-3 Orion	Lockheed	P-3A	25,000	2,000	7.5	13,600	33.0	WFF
Skyvan	Short Bros	SC-7	15,000	650	4.0	5,000	2.8	WFF
Sabreliner	Rockwell	T-39	41,000	1,400	3.2	1,500	3.0	WFF
Helicopter	Bell	UH-1B	10,000	450	4.5	2,000	3.5	WFF
Lear Jet	Gates Lear Jet	23-049	41,000	1,000	3.0	750	4.0	SSC

Aircraft performance values vary with payload, altitude, air temperature, weather conditions, mission type and duration.

Instruments Available (Core Instruments)
NASA Aircraft

Instrument	*Aircraft*
Ames Research Center	
Scanners/Radiometers	
NS-001-Thematic Mapper Simulator - 8 Channels	C-130B
Daedalus-Thematic Mapper Simulator* - 11 Channels	ER-2/U-2
Linear Array Scanner* - 1 Channel	ER-2/U-2
PRT-5 Radiometer - 1 Channel	DC-8/C-130B
Cameras	
Metric - 6" and 12"	ER-2/U-2/DC-8/C-130B
Panoramic	ER-2/U-2/DC-8
High-Resolution Special (Panoramic)	ER-2/U-2
General Support	DC-8
Telescopes	
91-cm	C-141
30-cm	Learjet
Wallops Flight Facility	
All instruments provided by investigators	
Stennis Space Center	
Calibrated Airborne Multispectral Scanner	Learjet
Thermal Infrared MultispectralScanner	Learjet

** Real-time data link capability*

Investigator-Supplied Instruments Currently in Use - NASA/WFF

Aircraft	*Instrument*	*Investigator/Inst.*
Navigation & Environmental Monitoring System	Airborne Oceanographic Lidar	Krabill
	Surface Contour Radar	Walsh
	Ku Band Ocean Wave Spectrometer	Jackson
	MOCSS Ocean Data Acquisition System	Oberholtzer
	Infrared Lidar	Bufton
	Rain Radar	Nakamura
Electra	GTE Instrument Package	Hoell
	Differential Absorption Lidar	Browell
	Laser Altimeter	Abshire
	Pressure Temperature Lidar	Korb
	Aerosol Gas Experiment (SAGE II)	
Skyvan	Advanced Solid State Array Spectrometer	Irons
T-39	Laser Altimeter	Bufton

Investigator-Supplied Instruments Currently In Use - NASA/ARC

Aircraft	*Instrument*	*Investigator/Inst.*
ER-2/U-2	Cloud Lidar System	Smith/U. Wisc
	Advanced Microwave Moisture Sensor	Wilheit/GSFC
	Microwave Cloud Radiometer	Smith/U. Wisc
	Multispectral Atmospheric Mapping Sensor	Smith/U. Wisc
	Microwave Temperature Sounder	
	High Resolution Interferometer Sounder	
	Cloud Top Scanner	
	Lightning Sensors	
	STEP Instrument Package	Russell/ARC
	Advanced Visible/Infrared Imaging Spectrometer	Vane/JPL
DC-8	L-C Band Synthetic Aperture Radar	Elachi/JPL
	Advanced Microwave Moisture Sensor	Wilheit/GSFC
	CO_2 Pulsed Laser	Fitzjarrald/MSFC
	AMMR?	Wilheit/GSFC
	Electrically Scanning Microwave Radiometer	Wilheit/GSFC
	GATE/GTE Instrument Package	
C-130	AMSCAT Ku-Band Scatterometer	Li/JPL
	Advanced Solid State Array Spectrometer	Kim/GSFC
	Pushbroom Microwave Radiometer	Wang/GSFC
	Sun Photometer	Wrigley/ARC

NASA Research Aircraft Payload Accomodations

Aircraft	*Equipment*
ER-2	Q-Bay Instrumentation Area and Payload Pallets (Pressurized) Wing-Mounted Instrumentation Pods (Pressurized) Nose Cone Instrumentation Area (Pressurized) Zenith and Nadir Viewing Capability
U-2	Q-Bay Instrumentation Area and Payload Pallets (Pressurized) Wing-Mounted Instrumentation Pods (Pressurized) Nose Cone Instrumentation Area (Pressurized) Zenith and Nadir Viewing Capability
DC-8	Heliostat-Gyro Stabilized Mirror System Sensor Viewports at Nadir; 8°, 40°, and 65° Elevations, and Zenith General Purpose Underbelly Pylon and Antenna Housing Wing Tip Pylon Optical Windows Liquid and Gaseous Nitrogen System 19-Inch Panel Equipment Racks
C-130	Need information
C-141	91-cm Aperture Infrared Telescope Facility. Sensors at Telescope Focus are Provided and Operated by the Investigator. Navigational and Environmental Data: Recorded Automatically for Each Flight and Made Available to Investigators.
Learjet	

Ames Research Center Aircraft General Support Equipment

Systems	*Aircraft*
Dew/Frost Point Hydrometer	DC-8
Radar Altimeter	DC-8/C-130B
Weather Radar	DC-8/C-130B/Learjet
Inertial Navigation	All Aircraft
Time Code Generator	All Aircraft
Closed Circuit Television	DC-8/C-130B
Heliostat	DC-8/Learjet
Water Vapor Overburden	C-141
Data Acquisition Systems	DC-8/C-130B/C-141
Data Facilities	ER-2/U-2/DC-8/C-130B/C-141
Data Distribution System	DC-8

NASA Airborne Program Instruments & Experiments Glossary

ABLE	Atmospheric boundary Layer Experiment
ADLS	Airborne Doppler LIDAR System
AMPR	Advanced Microwave Precipitation Radiometer
AOL	Airborne Oceanographic Lidar
ARMAR	Airborne Rain Mapping Radar
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
C-SCAT	C-Band Scatterometer
COMM	Commercialization Flights
CITE	Chemical Instrumentation Test and Evaluation
EOS	Earth Observations Systems (Space Station)
ESMR	Electrically Scanning Microwave Radiometer
FIFE	First ISLSCP Field Experiment
FIRE	First ISCCP Regional Experiment
GALA	Geoscience Airborne Laser Altimeter
GLOBE	Gobal Backscatter Experiment
GLRS	Geodynamics Laser Ranging & Altimetry System
GOFS	Global Ocean Flux Study
HRIS	High Resolution Interferometer Spectrometer
JOPE	Joint Participation Experiment
Laser Alt	Laser Altimeter
LIDAR	Light Imaging Doppler Aircraft Radar
MAC	Multisensor Aircraft Campaign
MPR	Microwave Precipitation Radiometer
MR	Microwave Radiometer
MRA	Multibeam Radar Altimeter
NUSCAT	KU-Band Scatterometer
PIS	Polar Ice Surveys
SAGE	Stratospheric Aerosol and Gas Experiment
SAR	Synthetic Aperture Radar
SCANSCAT	Scanning Scatterometer
SIR-C	Shuttle Imaging Radar-C
SLAP	Shuttle Laser Altimiter Program
SSM/I	Special Sensor Microwave Imager
STEP	Stratospheric -- Tropospheric Exchange Project
SWADE	Surface Wave Dynamics Experiment
TRACE	Transport and Chemistry Near the Equator
TIIS	Thermal Infrared Imaging Spectrometer
TIMS	Thermal Infrared MultiSpectral Scanner

Instrumentation Thrusts in NASA Airborne Science

Aircraft	*Instrument*	*Discipline*
ER-2	Advanced Microwave Precipitation Radiometer (AMPR)	Atmosphere
	Advanced Visible-IR Imaging Spectrometer (AVIRIS)	Land
	High Resolution Interferometer Spectrometer (HRIS)	Atmosphere
	Lightning Research Pallet	Atmosphere
	Microwave Precipitation Radiometer (MPR)	Atmosphere
	Thermal Infrared Multispectral Scanner (TIMS)	Land
DC-8	Aerosol Sampling Probes	Atmosphere
	Airborne Doppler LIDAR System (ADLS)	Atmosphere
	Airborne Rain Mapping Radar (ARMAR)	Atmosphere
	CO2 Backscatter LIDAR	Atmosphere
	CO2 Isotope Focused CW Laser	Atmosphere
	CO2 Pulsed Laser	Atmosphere
	Synthetic Aperture Radar (C,L,P Bands) (SAR)	Land, Oceans
	Visible/Near IR Backscatter LIDAR	Atmosphere
	(JPL) Mark IV Interferometer	JPL
C-130	C-Band Scatterometer (C-SCAT)	Oceans
	KU-Band Scatterometer (NUSCAT)	Oceans
	Thermal Infrared Imaging Spectrometer (TIIS)	Land
Electra	Raman LIDAR Moisture Sounder	Atmosphere
P-3	Multibeam Radar Altimeter (MRA)	Oceans
Skyvan	Geoscience Airborne Laser Altimeter (GALA)	Land

Instruments Related to Space Station/EOS

Airborne SAR for Synthetic Aperture Radar
ASAS for Moderate Resolution Imaging Spectrometer
AVIRIS for High Resolution Imaging Spectrometer
TAL-BR for High Resolution Multifrequency Microwave Radiometer
TIMS for Future Thermal Infrared Sensor
TMS for Future Thermal Infrared Sensor

Future Thrusts in NASA Airborne Earth Science Investigations

		FY 1990	FY 1991	FY 1992
ATMOSPHERE	*ER-2*	FIRE Latitude Surveys(STEP)	FIRE (TBD) Latitude Surveys(STEP) Ozone Hole(Antarctic)	
	DC-8	GLOBE II	Ozone Hole (Antarctic)	
	Electra	ABLE-3B PT-LIDAR CITE-4 GTE		
OCEANS	*DC-8*	Polar Ice Surveys/SAR (Antarctic)	Polar Ice Surveys/SAR Laser Alt. (Antarctic)	Polar Ice Surveys/SAR Laser Alt. (Antarctic)
	P-3	Laser Alt (Greenland) GOFS II EOS Simulation	GLRS SWADE (N.Atlantic) EOS Simulation	GLRS EOS Simulation
	C-130		SWADE (N.Atlantic) ERS Validation	STORM SCANSCAT Dev.
LAND	*ER-2*	AVIRIS Surveys MAC-Europe Comm Flights	AVIRIS Surveys Comm Flights	AVIRIS Surveys
	DC-8	SAR Surveys/Pre SIR-C (Greenland) MAC-Europe	SAR Surveys SIR-C Underflight	SAR Surveys
	C-130	TIMS Surveys EOS Simulation MAC--Europe Comm Flights FIFE	TIMS Surveys EOS Simulation Comm Flights FIFE	EOS Simulation
	T-39	Laser Alt Surveys SLAP	SWADE	
	UH-1	FIFE FED	FIFE	

B-3.

NOAA Research Aircraft Performance Characteristics and Instrumentation

NOAA/OAO WP3D N43/42RF
Aircraft Instrumentation Specifications

Variable measured	Instrument Type	Manufacture & Model No	Range	Resolution	Accuracy	Data Recording
Aircraft position (lat,lon)	Loran C Navigation	Advanced Navigation,Inc ANI-7000	Dependent* on Loran coverage	0.0008° (lat,lon)	0.19Km (lat,lon)	RAMS
	Integrated Nav. system with two Delco intertials,	INS Delco Corousel IVA	Worldwide	0.0014° (lat,lon)	2 - 3 miles RMS	RAMS
Aircraft Position (lat,lon)	Omega receiver	Northrop NDC-1070 Omega Receiver/Computer	Worldwide		Dependent on location 4-6 mi RMS	RAMS, ASDL
	and a Doppler velocity sensor	Teledyne APN 213	0 - 400 m/s		0.5 ms -1/hr	RAMS, ASDL
Pitch	wander azimuth stable platform inertial reference system	Delco Carousel IVA	± 45°	0.005°	≤ 1.0 nmi/hr	
Roll			± 45°	0.005°		
Drift Angle(comp)			± 45°	0.005°		
Heading			0 - 359°			RAMS
East Velocity			0 - 400 m/s			
North Velocity			0 - 400 m/s			

* Not Worldwide Coverage

NOAA / OAO WP3D N43 / 42RF
Aircraft Instrumentation Specifications

Variable Measured	Instrument Type	Manufacture & Model No	Range	Resolution	Accuracy	Data Recording
Ground speed Track Angle	Doppler Velocity Sensor	Teledyn APN 213	0-400 m/s 0-360°		0.5 ms^{-1}/hr	RAMS
Pressure (Static)	Wingtip Pitot	Garrett # 2100776-2-2	102-1219 mb	0.04 mb	0.2mb or 0.02% whichever is >	RAMS
	Fuselage Pitot	Rosemount # 542K2	-1000 to 40,000 ft	0.02 mb	± 0.5 mb	RAMS, ASDL
Pressure (Dynamic)	Wingtip Pitot Sensor	Garrett # 2100774-2-2	3.4 to 406 mb	0.03 mb	0.1+0.0423P mb	RAMS
	Fuselage 1	Rosemount # 542K2	9-213 mb	0.03 mb	± 0.5 mb	RAMS, ASDL
	Fuselage 2	Rosemount #1221F1AF113113	0-345 mb	0.005 mb	± 1.1 mb (± 0.5 mb)	RAMS
Geopotential Altitude	Radar Altimeter	Stewart Warner #APN-159	15,000 m	1 meter	3m or 1% whichever is >	RAMS, ASDL
Cloud Liquid Water	Resistance Wire	Johnson Williams LWH	0-6 gm/m^3	0.001gm/m^3	± 10%	RAMS, ASDL
Cloud Liquid Water	Hot Wire	CSIRO King L.W.	0-6 gm/m3	0.001gm/m3	±10%	RAMS

NOAA/OAO WP3D N43/42RF
Aircraft Instrumentation Specifications

Variable Measured	Instrument Type	Manufacture & Model No	Range	Resolution	Accuracy	Data Recording
Angle of Attack Differential Pressure	Differential Pressure Transducer	Rosemount 1301 B	± 100 mb	0.003 mb	0.5 mb	RAMS
Angle of Attack Dynamic Pressure		Rosemount 1301 D	0-250 mb	0.007 mb	0.5 mb	RAMS
Sideslip Differential Pressure	Differential Pressure Transducer	CIC 8600-5 AP, BP	± 137.5 mb	0.004 mb	1 mb	RAMS
Sideslip Dynamic Pressure		CIC 8600-5 DAP, DBP	± 275 mb	0.008 mb	2 mb	RAMS
Total Air Temperature	Platinum Wire Resistance	Rosemount 102CH2AF	-90°C/250°C	0.01°C	± 0.29°C	RAMS, ASDL
Dewpoint (Frost)	Cooled Mirror Hygrometer	General Eastern 1200 Series	-90°C/50°C	0.005°C	± 1.0°C	RAMS, ASDL
Sea Surface Temperautre	Infrared Radiometer	Barnes Model PRT-5	-20°C/75°C	0.05°C>0°C	± 0.5°C	RAMS
CO_2 Absorption Temperature			-42°C/30°C	0.10°C,<0°C		
Upward Looking Temperature			Selectable			

NOAA/OAO WP3D N43/42RF
Aircraft Instrumentation Specifications

Variable Measured	Instrument Type	Manufacture & Model No	Range	Resolution	Accuracy	Data Recording
Horizontal Radar Reflectivity	Nose PPI C-Band Lower Fuselage C-Band	Collins WRT-701C Videotranics	± 40° elev 180° Azimuth 320 nmi	5.4°x5.4° beam 1.1°x4.1°x 1.55 nmi		ASDL Radar Data System
Radar Reflectivity	Lower Fuselage C-Band Color Weather Radar	Sigmet	360° Azimuth 200 nmi ± 10° elev			
Vertical Radar Reflectivity	Tail Radar X-Band		360° Azimuth 50 nmi Perpend to Track	1.9°x1.4° beam		ASDL Radar Data System
Doppler Radar	Tail Radar X-Band		360° Azimuth 50 nmi Perpen to Track	12.9 m/s before folding		Doppler Recording System
Spectral Width Velocity	Tail X-Band Doppler Color Weather Radar	Sigment				
Visible Radiation	Pyranometer Uplooking Downlooking	Eppley PSP, 8-48	0-2800 watts m^{-2} 0-1400 watts m^{-2}		± 1% ± 2%	RAMS
Infrared Radiation	Pyrgeometer Uplooking Downlooking	Eppley PIR	0-700 watts m^{-2}	5μv/wm^{-2}		RAMS

NOAA / OAO WP3D N43 / 42RF
Aircraft Instrumentation Specifications

Variable Measured	Instrument Type	Manufacture & Model No	Range	Resolution	Accuracy	Data Recording
Air Haziness	Nephelometer	Alquist	10^{-8} to 10^{-2} m^{-1}	10^{-7} m^{-1}		
Air Constituents	Adiabatic Air Manifold	OAO	Numerous Ports Available for Gas Sampling Instruments			
Ocean Temperature Profiles	Airborne Expend. Bathythermograph System	SSQ-36 with System Receiver Unit	-2°C to +35°C	0.1°C		RAMS, ASDL
**Ambient Pressure Ambient Temp Relative Humidity Mean Layer Winds	Airborne Expend. Omega Dropwind-sonde system	Tracor	150-1060 mb -50°C-40°C 10-100%	1 mb 0.1°C 1% 1 m/s	± 2 mb ± 2°C ± 10%	ODW Record ASDL
Ambient Pressure Ambient Temp Relative Humidity Mean Layer Winds	Loran Dropwind-sonde (LDW)	NCAR	150-1060 mb -50°C-40°C 10-100%	1 mb 0.1°C 1% 1 m/s	+ 2 mb + 2°C + 10%	
Photography	16mm time lapse 0.5,1,2,5sec/frame			.5,1,2,5 sec/frame		
Cloud Droplet Spectrum	Laser light scatter with photodiode array	PMS OAP-2D-C	25-800 μm	25μm @ 100 m/s	50 μm @ 100 m/s	PMS Data System
Small Cloud Droplet Spectrum	Linear, photodiode optical array (FSSP)	PMS FSSP-100	0.5 - 45μm	2 μm	2μm or 10% whichever is >	PMS Data System

NOAA/OAO WP3D N43/42RF
Aircraft Instrumentation Specifications

Variable Measured	Instrument Type	Manufacture & Model No	Range	Resolution	Accuracy	Data Recording
Hydrometer size Spectrum	Laser light scatter with photodiode array	PMS OAP-2D-P	200-6400 μm	200 μm @ 100 m/s	200 μm @ 100 m/s	PMS Data System
Aerosol Size Spectrum	ASASP Laser Cavity light Scattering with Photo Detector	PMS ASASP-100X	0.12-3.12 μm	.25 μm		PMS Data System
Ice Accumulation	Vibrating Probe	Rosemount #871FA	Deices and outputs 5 vdc signal upon accumulation of 0.02" of ice			RAMS, ASDL

NOAA/OAO WP3D N43/42RF
Aircraft Instrumentation Specifications

Variable measured	Instrument Type	Manufacture & Model No	Range	Resolution	Accuracy	Data Recording
Electric Field	Upper and lower Field Mills	Owned by Desert Research Institute				
Ocean Current Profiles	Airborne Expend. Current Probe	Owned by AOML/HRD				
Surface Spray	Stepped Frequency	Tanner				
Surface Wind Speed	Microwave Radiometer (SFMR)	Owned by the University of Massachussetts		1 knot		RAMS
Photography	70 MM time lapse (N43RF only)	Hasseblad		1 frame/ 5 sec.	High Resolution	
Cloud Total Water	Contant Temp. Heated Wire	PMS CSIRO King Probe Owned by ERL	0-6 gm/m^3	0.006 gm/ m^3		RAMS
Ice Particles	Film Replicator	Formvar Owned by AOML/HRD	1-1000 um	Dependent on Coating Thickness		Mylartape

OAO King Air BE-90 N46RF
Aircraft Instrumentation Specifications

VARIABLE MEASURED	SYMBOL	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Aircraft Position	LAT LON (TAS,WS,WD)	Loran-C System*	Advanced Navigation, Inc. ANI-7000	± 90°	0.19Km (Location dependent)	0.0002*
Aircraft Position	LAT LON	Distance Measuring* Equipment (DME) (Slant Range)	King Radio, KDM 7000 DME	0 + 24 km (Alt. dependent)	Geometry & reception dependent	0.0002*
Static Pressure		Oscillation Frequency (digital output)	Rosemount, Inc. 1501	250 to 1035 mb	± 1mb	0.1mb
Total Air Temperature		Platinum Wire	Rosemount	- 40°C to + 40°C	± 1.0°C	0.1°C
Dew Point Temperature		Hygrometer	General Eastern	- 75°C to + 50 °C	± 1.0°C	0.1°C
Cloud Liquid Water Content		Hot-Wire	PMS-King Probe	0-6g/m^{-3}	± 0.1g/m^{-3}	0.1g/m^{-3}
Cloud Water		Slotted Rod	Mod. Mohnen	.5μm		
Cloud Particle Size Distribution		Laser Particle Spectrometer	Particle Measuring Systems, Inc. ASASP-100X PMS FSSP-100 PMS OAP 2D-C	0.12-3.12μm 0.5-47μm 25-800μm		

* Not Worldwide Coverage

OAO King Air BE-90 N46RF
Aircraft Instrumentation Specifications

VARIABLE MEASURED	SYMBOL	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Solar Irradiance		Photometer	LI-COR	0-1500Wm^{-2}		1Wm^{-2}
Gas Analyses H_2O_2 NO/NO_4 Os SO_2		Florescence Chemiluminescence U.V.Photometric Pulsed Florescent	K + K Ent. TECO 14B TECO 49 TECO 435	+0-50ppbv 0-1000ppbv 0-1000ppbv 0-100 ppbv	0.1 ppbv 0.1 ppbv 2.0 ppbv 0.1 ppbv	0.1 ppbv 0.07ppbv 1.0 ppbv 0.05ppbv
Filter Packs	Aerosol Collection	NOAA/AQG				
Data Acquisition		Computer Digital Processing Strip Chart	Compaq PMS HP	0-10v	0.01v	0.01v

OAO Cessna Citation N52RF
Aircraft Instrumentation Specifications

VARIABLE MEASURED	SYMBOL	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Aircraft Position (Lat, Lon)		Loran C Navigation	Texas Inst. 9100	Dependent * on Loran Coverage	0.19km (Lat, Lon)	0.0008°*
Aircraft Position		Distance Measuring Equipment (DME)		0 + 24 km (Alt. dep)	Geometry & Reception Dependent	0.0002*
Geodotential Altitude		Radar Altimeter	Stewart Warner	0-2500 Ft.		1m
Color Weather Radar		Digital (Non-recording)	RCA	2.5-140nm		
Dual Aerial Cameras		RC-10 Camera with Remote NF-2 Nav Drift Sight	Wild			High
** (ODW)	See WP3 Aircraft Instrumentation Specifications					

* Not Worldwide Coverage

OAO Shrike (AC-500) N47RF
Aircraft Instrumentation Specifications

VARIABLE MEASURED	SYMBOL	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Aircraft Position (Lat, Lon)		Loran C Navigation	Texas Inst. 9100	Dependent* on Loran Coverage	0.19km (Lat, Lon)	0.0008°*
Aircraft Position		Distance Measuring Equipment (DME)		0 + 24km (Alt. Dep)	Geometry & Reception Dependent	0.0002*
Geodotential Altitude		Radar Altimeter	Stewart Warner	0-2500 Ft.		1m
Nose B/W Weather Radar		Digital (Non-Recording)	RCA	2.5-140nm		
Aerial Cameras		Wild RC-8 Camera	RCA			High

* Not Worldwide Coverage

OAO Shrike (AC-500) N51RF
Aircraft Instrumentation Specifications

VARIABLE MEASURED	SYMBOL	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Aircraft Position (Lat, Lon)		Loran C Navigation	Navstar	Coverage Dependent	0.19km (Lat, Lon)	0.0008*
Aircraft Position		Distance Measuring Equipment (DME)		0 + 24km (Alt. Dep)	Geometry & Reception Dependent	0.0002*
Geopotential Altitude		Radar Altimeter	King Gold Crown	0-2500 Ft.		01 meter
Monochrome Nose Weather Radar		Digital (Non-Recording)	Bendix	2.5-140nm		
Snow/Water Equivalent		Airborne Gamma Radiation	EG & G	0-60cm of Water	0.75cm	
Soil Moisture		Airborne Gamma Radiation	EG & G	0.05mev 5.1mev	0.04rms	

* Not Worldwide Coverage

OAO Twin Otter (DHC-6-300) N48RF
Aircraft Instrumentation Specifications

VARIABLE MEASURED	SYMBOL	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Aircraft Position (Lat, Lon)		Loran C Navigation	Texas Inst. 9100	Dependent* on Loran Coverage	0.19km (Lat, Lon)	0.0008^{0}*
Aircraft Position		Distance Measuring Equipment (DME)		0+24km (Alt. Dep)	Geometry & Reception Dependent	0.0002*
Aircraft Position		VLF/Omega (RNAV)	Global Navigation GNS-500A			
Geodotential Altitude		Radar Altimeter	Stewart Warner	0-2500 Ft.		1m
Nose Color Weather Radar		Digital (Non-recording)	RCA	2.5-140nm		
Aerial Cameras		RC-10 Camera W/NF-2 Nav. Drift Sight	Wild			High

* Not Worldwide Coverage

OAO Turbo Commander (AC-690) N57074
Aircraft Instrumentation Specifications

VARIABLE MEASURED	SYMBOL	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Aircraft Position (Lat, Lon)		Loran C Navigation	Texas Inst. 9100	Dependent* on Loran Coverage	0.19km (Lat, Lon)	0.0008°*
Aircraft Position		Distance Measuring Equipment (DME)		0 + 24km (Alt. Dep)	Geometry & Reception Dependent	0.0002*
Geodotential Altitude		Radar Altimeter	Stewart Warner	0-2500 Ft.		1m
Nose B/W Weather Radar		Digital (Non-recording)	RCA	2.5-140nm		
Aerial Cameras		RC-10 Camera W/NF-2 Nav. Drift Sight	Wild			High

* Not Worldwide Coverage

OAO Cessna 210 N49RF
Aircraft Instrumentation Specifications

VARIABLE MEASURED	SYMBOL	INSTRUMENT TYPE	MANUFACTURER & MODEL NO.	Combined Performance of Transducer, Signal Conditioning, and Recorder		
				Range	Accuracy	Resolution
Aircraft Position		Loran-C System*	Advanced Navigation, Inc. (ANI-7000)	$\pm$ 90° $\pm$ 180°	0.19km (Location Dependent)	0.0002*
Aircraft Position		Distance Measuring Equipment (DME) (Slant Range)		0 + 24km (Alt Dep)	Geometry & Reception Dependent	0.0002*
Chaff Dispenser		Radar Chaff Dispersal	OAO			
Panoramic Cameras		KA-85A Vert/Forward Cameras	Enviro POD			High

* Not Worldwide Coverage